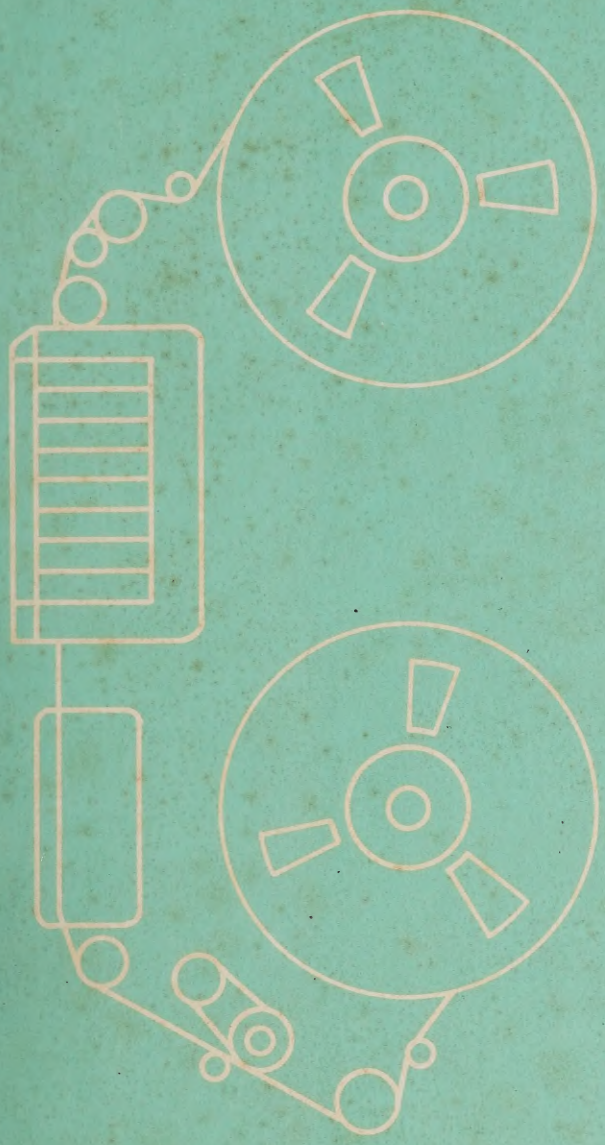

Servomechanisms

in the RCA TV TAPE recorder

SERVOMECHANISMS

in the

RCA TV TAPE RECORDER

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INTRODUCTION TO SERVOMECHANISMS

In the RCA Television Tape Recorder, three separate servo systems are used to (1) control the speed of the head-wheel motor, (2) control the speed of the capstan motor, and (3) control the position of the tape guiding shoe, which in turn controls the pressure with which the video recording heads bear against the tape. The operator of a television tape recorder need not have a complete understanding of the highly sophisticated details of servomechanism design, but he will probably find it helpful to have at least superficial knowledge of some of the more basic principles of servo systems. The purpose of this article is to present these principles in terms already familiar to broadcast engineers.

In general, any system employing automatic control may be regarded as a servo system (the word *servo* literally means *slave).* The term *servomechanism* usually refers to a servo system in which at least a portion of the system is mechanical in nature, but servo systems in general may include mechanical, hydraulic, pneumatic, thermal, or electronic devices in a wide variety of combinations. A number of familiar circuits used for automatic gain control or automatic frequency control are actually all-electronic servo systems. One of the most familiar types of servo systems is the thermostatically-controlled heating plant in a dwelling. Most of the broad principles of servo design may be explained by reference to such familiar examples.

Servo systems are commonly divided into two categories known as "closed-loop" and "open-loop" systems. The great majority of systems are of the closed-loop type, in which automatic control is achieved through the application of the well-known feedback principle. In any closed-loop system, there is an error detector of some sort in which the output of the system is compared against the desired performance characteristic. The error "signal" produced by this detector then controls the output in such a way as to tend to minimize the error. Figure S-1 is a generalized block diagram for a closed-loop servo system. In the servomechanisms used in the RCA Television Tape Recorder, the output devices happen to be electric motors and the error detectors and amplifiers are electronic circuits, but the same principles would apply if the system used very different devices. For example, the error detector might be a pressure transducer, the "amplifier" might be a hydraulic valve, and the output device might be a hydraulic cyclinder.

The nature of the error detector depends to a large extent upon the objective of the servo system. If the objective of the system is to make the output respond faithfully to variations in the input, as in the case of the ordinary feed-back stabilized amplifier or an automatic-frequency-control system, then the error detector consists of a circuit or device for comparing the output directly with the input. If, on the other hand, the objective of the automatic control system is to maintain a uniform output in spite of possible fluctuations at the input or in the environment, the error detector consists of some device to measure or compare the output against some relatively fixed "standard condition." For example, the objective of the automatic heating plant in a dwelling is to maintain a uniform room temperature in spite of fluctuations in the outside temperature, and the error detector is a bi-metallic element in a thermostat which senses whether the room temperature is above or below a predetermined value. Likewise, the objective of the automatic-gain-control system in a television receiver is to deliver a constant signal level at the output of the video detector in spite of fluctuations in the level of the input signal, and the error detector consists of a rectifier which senses whether the level of the output signal is above or below normal.

In a so-called "open-loop" servo system, there is no application of the feedback principle, and automatic control is achieved without direct reference to

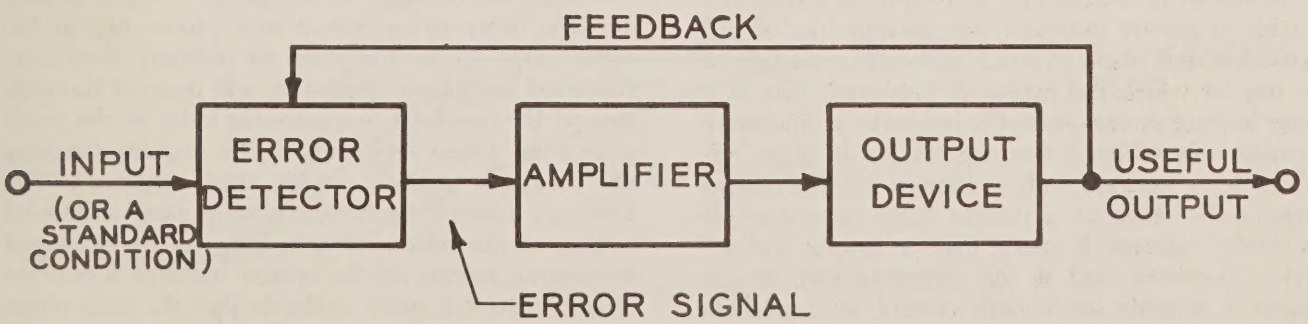

Figure S-1. Generalized Block Diagram for a Closed-Loop Servo System

the output. Since the servos in the RCA Television Tape Recorder are all of the closed-loop type, a detailed discussion of the open-loop type is not warranted, but one simple illustration may be helpful. It is possible (though not very practical) to design an automatic heating control system in which the temperature sensing device is located out-of-doors where it is not influenced by the system output (i.e., the indoor temperature). Such a system could actually be reasonably effective if it included an appropriate programming device between the temperature sensing element and the heating plant itself. For example, the system could be designed so that the furnance would run only five minutes of each hour if the outside temperature is, say 60 degrees, but would run 50 minutes of each hour if the outside temperature drops to 10 degrees. Such an open-loop system would have no automatic compensation for such unpredictable factors as wind velocity and direction, or open doors and windows, unless additional sensing elements were built in to detect these factors. In general, open-loop servo systems are not very suitable for applications where the output is influenced by a number of variables.

Servo systems are further classified into "off-on" and "continuous" types. The usual home heating plant is a good example of the "off-on" type. When the room temperature drops below a predetermined value, the thermostat closes a circuit which causes the burner to operate at a constant rate until the temperature rises above another predetermined value. At any given instant, the active element in the system is either running or not running, depending upon the information supplied by the error detector. A simple heating plant is a one-way system in that it is actively "driven" only in the direction of increasing temperature — reductions in temperature occur only as a result of relatively uncontrolled heat losses. The system could be modified for two-way operation by the addition of air-cooling equipment which would be operated automatically to prevent the temperature from exceeding a predetermined value. In such a system, the error detection devices would determine the direction of correction as well as the "off-on" information.

The so-called "continuous" servo systems are usually capable of greater precision than comparable "off-on" types, because they provide continuous control of the *rate* at which the output is produced. Just as a home heating system normally holds the temperature constant only within a few degrees, so do most "off-on" systems operate only within a predetermined range, rather than at a precise value of output. If the error detector is more than a simple "off-on" device, however, and if the output device in the system is suitable for smooth control, it is possible to make significant reductions in the maximum error. A highly advanced type of home heating system might, for example, employ a gas burner in which the flow of fuel is controlled by the position of a continuously-variable bi-metallic element in the room thermostat. Such a system could, in theory, be designed so that the burner operates continuously at the rate which exactly balances the heat losses in the dwelling, thus holding an absolutely constant room temperature. In practice, the temperature stability would depend upon a number of factors, including the thermal inertia of the system and the sensitivity of the thermostat-valve combination. A more familiar example of a "continuous" servo system is the automatic gain control circuit in a radio receiver. The extent to which the continuously-developed error signal in a radio age system maintains a uniform output depends primarily upon the gain available in the feed-back loop. The automatic gain control and synchroguide circuits used in television receivers are also examples of continuous servo systems, but they both happen to be of the "sampled data" type. They receive input data at a line-frequency rate, but then integrate or "smooth out" the error signal to exercise continuous control over the output.

All closed-loop servo systems are subject to two hazards which can be avoided only by careful design and proper operation. These hazards are oscillation and the phenomenon known as "hunting." The possibility of oscillation exists because of the presence of a feedback loop. The objective, of course, is to employ only *negative* feedback, which serves to stabilize the system, but in all practical systems it is impossible to maintain a uniform phase shift for all frequency components handled through the feedback loop. Electronic amplifiers are used in many systems, and it is well-known to broadcast engineers that there is always a phase shift associated with both the low- and high-end roll-off characteristics in a-c-coupled amplifiers. The low-frequency phase shift can be eliminated by the use of direct coupling (which introduces other problems), and the high-frequency phase shift can be modified (though not completely eliminated) by phase-compensation techniques. It may not be quite as well understood that there are also phase shifts involved in the electro-mechanical portion of a feedback loop. The inertia of a rotating motor, for example, will tend to prevent instantaneous response to a change in input power, and the delay is equivalent to a phase shift in the servo loop. As in the case of ordinary feedback-stabilized amplifiers, oscillation will occur if the gain around the feedback loop exceeds unity at the point where the phase shift equals 180 degrees (making the feedback positive, rather than negative). The tendency toward oscillation usually puts a definite ceiling on the maximum gain that can be employed in a servo system. If the system involves a number of elements, it is quite probable that the total phase shift adds up to 180 degrees at some point within the frequency-response band of the system; such a system will remain stable only if the maximum gain

is low enough to keep the gain at the frequency corresponding to 180 degrees phase shift less than unity.

The term "hunting" is commonly used in reference to a form of limited-range oscillation in a servo system in which the output fluctuates slightly above and below the desired output level. Hunting is inherent in many types of "off-on" servos where continuous losses are involved, as in the case of a home heating plant. In well-designed continuous systems, however, hunting should occur to a significant degree only for a short period after a sudden change in the input to the system. The response characteristics of servo systems are frequently tested by applying a deliberate sudden change to the input and observing the output response. Representative response curves are shown in Figure S-2. If the damping in the system, both electrical and mechanical, is adjusted to a critical value, the output response will move smoothly from the original to the new value at a rate which is dependent upon the gain and the intertia in the system (the more gain, the faster the response; the more inertia, the slower the response). If there is excessive damping, the time required for the system to make the adjustment is considerably increased. If the damping is less than the critical value, the response changes more rapidly, but it overshoots the desired level and then oscillates (or "hunts") for a limited period of time around the desired output value. If the damping is reduced to zero, the hunting would continue indefinitely, and the system would normally be considered quite unstable. In practice, a great many servo systems are designed to operate in the slightly underdamped condition, because the advantage of more rapid response at a given level of amplifier gain usually outweighs the disadvantage of the brief period of "hunting" before the system settles down after a sharp transient disturbance.

There are a number of factors in addition to amplifier gain, damping, and inertia which affect the response characteristics of a servo system. Backlash in the mechanical portion of an underdamped system, for example, can increase both the amplitude and the period of the overshoots, because the error signal is delayed slightly by the backlash. Another significant factor is limiting, which can occur in the detector, amplifier, or output device. In a servo system with limiting, the maximum rate of response is limited by some such factor as the maximum acceleration characteristic of the motor, and the system behaves in a linear fashion only for low-level or relatively slow transient disturbances. Limiting is not always objectionable – it is frequently employed deliberately as a means of achieving high gain in a narrow range without handling excessive maximum signal amplitude. It is important to note that the ratings of motors and amplifiers used in servo systems are determined not so much by the power level required to balance steady-state losses as by the power level required to achieve the desired acceleration characteristics when the system is subjected to sudden disturbances.

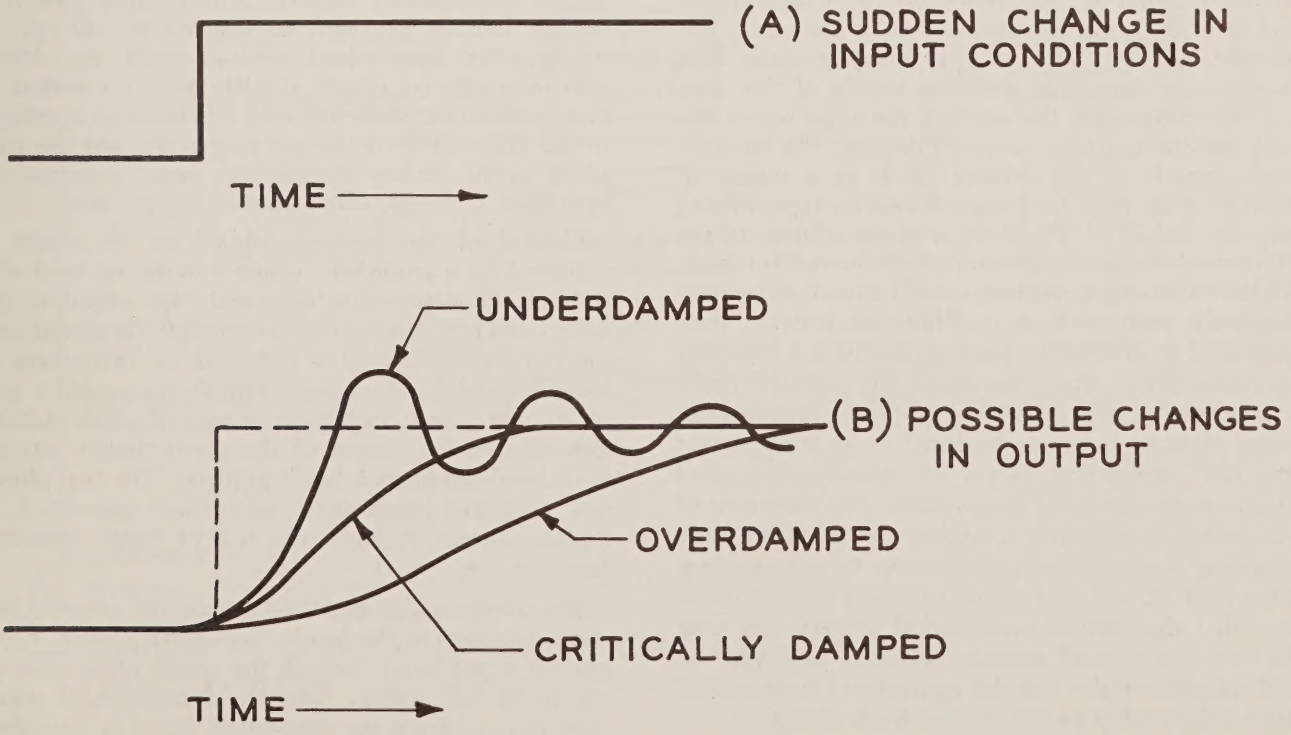

Figure S-2. Representative Transient Response Curves for Closed-Loop Servo Systems

HEAD-WHEEL SERVO SYSTEM

OBJECTIVES

The purpose of the head-wheel servo system is to control the speed of the head-wheel motor during both record and playback operation. In both cases, the nominal speed of the head-wheel motor is 240 revolutions per second (or 14,400 rpm), but it is desirable to exercise very tight control over this speed for reasons which are summarized below.

In the record mode, it is desirable to make the head-wheel speed in revolutions per second exactly four times the vertical scanning frequency (which is nominally 60 cycles per second). Because the timing reference for the television system may be derived from any one of several sources (including the power line, a sync generator crystal, or a color subcarrier oscillator), the most practical way to control the head-wheel speed is with a servo system in which an error detector compares the frequency and phase of a signal developed by a tone wheel attached to the head-wheel motor against a reference pulse derived from the signal itself. This action assures that each television field period occupies exactly sixteen complete transverse tracks on the tape (note that each revolution of the head wheel produces four tracks, because of the four heads around the circumference of the wheel).

If the head-wheel speed were set only at a nominal value of 240 rps with no direct comparison to the vertical scanning frequency, the relative phase of the television signal as laid down on the tracks would tend to drift slowly in one direction or the other. For example, the first vertical sync pulse in each field would occur sometimes near the middle of the tape, and sometimes near the edge of the tape where the head switching action occurs. Likewise, the 60-cycle pulse applied to the control track as a means of identifying the beginning of each field for tape splicing purposes would tend to drift in phase relative to the 240-cycle sine wave also recorded on the control track. While an individual machine could be made to operate effectively with such a condition of relative drift (provided no attempt is made to play back a tape that has been spliced after recording), the practical problems associated with tape splicing and the interchangeability of tapes between machines make it important that the head-wheel speed be closely controlled relative to the scanning frequencies. The statement of recommended operating practices for television tape recording currently being drawn up by a committee of the SMPTE will undoubtedly include recommendations that the vertical sync period be recorded near the center of a head scanning interval, and that the field reference pulse (or the equivalent) bear a fixed phase relationship to the control track signal.

In the playback mode, the speed of the head-wheel motor determines the absolute value of the deflection frequencies (and all other frequency components) in the reproduced signal, so it is important that the head-wheel speed be sufficiently constant that the scanning frequencies fall within the tolerance limits suitable for broadcast transmissions, and that the timing of complete programs is accurate enough to meet broadcast schedule requirements. To assure such stability, the head-wheel motor is controlled by the same servo system used for recording, but the reference signal compared with the tone-wheel signal in the error detector is derived either from a local sync generator or from the power line. (The former reference is preferred, but may not be available in all cases.)

OVERALL BLOCK DIAGRAM

A simplified block diagram of the head-wheel servo system is shown in Figure HW-1. The head-wheel motor itself is a synchronous, hysteresis type designed for operation in the vicinity of 300 cycles per second. It is not operated in a synchronous mode in the TRT-1A, however. It is supplied with 3-phase power at about 340 cycles per second, but its speed is held back to 240 revolutions per second by the servo system. This non-synchronous operating condition gives the servo system a good acceleration characteristic. The motor is continuously seeking to increase its speed toward synchronism at 340 revolutions per second, but is held back by the fact that the servo system continuously delivers only enough power to exactly balance the load at a speed of 240 rps. In theory, the head-wheel motor could be driven synchronously by power at 240 cps (as a matter of fact, provision is made for such synchronous operation in the RCA TRT-1A for test purposes), but the gain of a servo system depending upon synchronous operation is lower, other factors being equal.

Control of the power supplied to the motor is achieved by a modulator which adjusts the level of a 340-cps signal in accordance with the output of the error detectors. The modulator operates at a relatively low power level, so it is followed by two stages of feedback-stabilized voltage amplification and a pair of 70-watt power amplifiers. A pair of phase-shifting networks at the output of the servo chassis provide two signals 90 degrees apart in phase. The two phases are amplified separately, and then converted to 3-phase power through the use of Scott-connected transformers.

As shown in Figure HW-1, there are actually two error detectors in the head-wheel servo system. Close control is achieved through the phase error detector shown at the bottom, wherein a trapezoidal waveform derived from the tone-wheel signal is "sampled" by pulses derived from the stable reference source. (A trapezoid is used instead of the more common saw-

tooth waveform in order to obtain a steep slope in a narrow range in a signal with a reasonable peak-to-peak amplitude – the trapezoid may be regarded as a "slice" from a much larger sawtooth.) The precise control needed for normal operation results in a narrow lock-in range for the phase detector, so a wider-range velocity error detector is also used to reduce the time required for the servo system to assume control when operation is first started or momentarily interrupted. As will be shown presently, the velocity detector operates by measuring the period of the tone-wheel pulses. The outputs of both error detectors are combined in a mixing network and used to control a single modulator, but the detectors are cross-coupled in such a way as to minimize any tendency for the two detectors to supply conflicting information.

USE OF SIMPLIFIED SCHEMATIC DIAGRAMS

The circuit functions performed on the head-wheel servo chassis may be explained with the aid of a series of simplified schematic diagrams showing the various sections of the circuit. It should be made clear that these simplified schematics are not intended to replace the complete schematic diagram normally used as an aid in trouble-shooting or servicing. In the interests of clarity, details such as heater circuits, decoupling filters, and parallel combinations of resistors or capacitors have been omitted. Likewise, no attempt has been made to identify all components completely with designations, tolerances, and voltage ratings. All tubes have been identified with "V" numbers, however, to facilitate cross-checking between the simplified and the complete diagrams.

TRAPEZOID GENERATOR SECTION

Figure HW-2 shows the circuitry used to generate a trapezoidal waveform from the tone wheel pulse signal delivered by the tone-wheel amplifier. The first stage, V7A, is a conventional voltage amplifier with fixed bias, followed by a differentiating network which converts the pulse into a pair of negative and positive "pips". The negative pip, corresponding to the leading edge of the input pulse, is coupled through diode V8A to trigger a square-wave generator, multivibrator V12. This multivibrator is a stabilized, monostable type. In the "resting" condition, the left side of V12 is fully conductive and the right side is kept cut off with its cathode voltage held at nominally ground potential by a 1N34A diode. When a negative trigger pulse is applied to the plate of the right-hand side, however, the state of conduction reverses very rapidly, and the grid of the left-hand side is driven well below cutoff. The time constant which determines the length of time that the left side is cut off consists of the 1000-mmf coupling capacitor and the several resistors in series with it between ground and +B. This time constant is adjusted by the control marked "trapezoid balance" to make the output of V12 a symmetrical square wave. Output signals are taken from both plates of the multivibrator. The left side supplies a square wave to the velocity error detector for purposes which will be described later. The right side is coupled to a fixed-biased cathode follower, V7B, which is in turn connected to the trapezoid generator, V9. The peak-to-peak signal applied to the grid of V7B is more than adequate to make the cathode swing from cut-off to a conducting state which re-

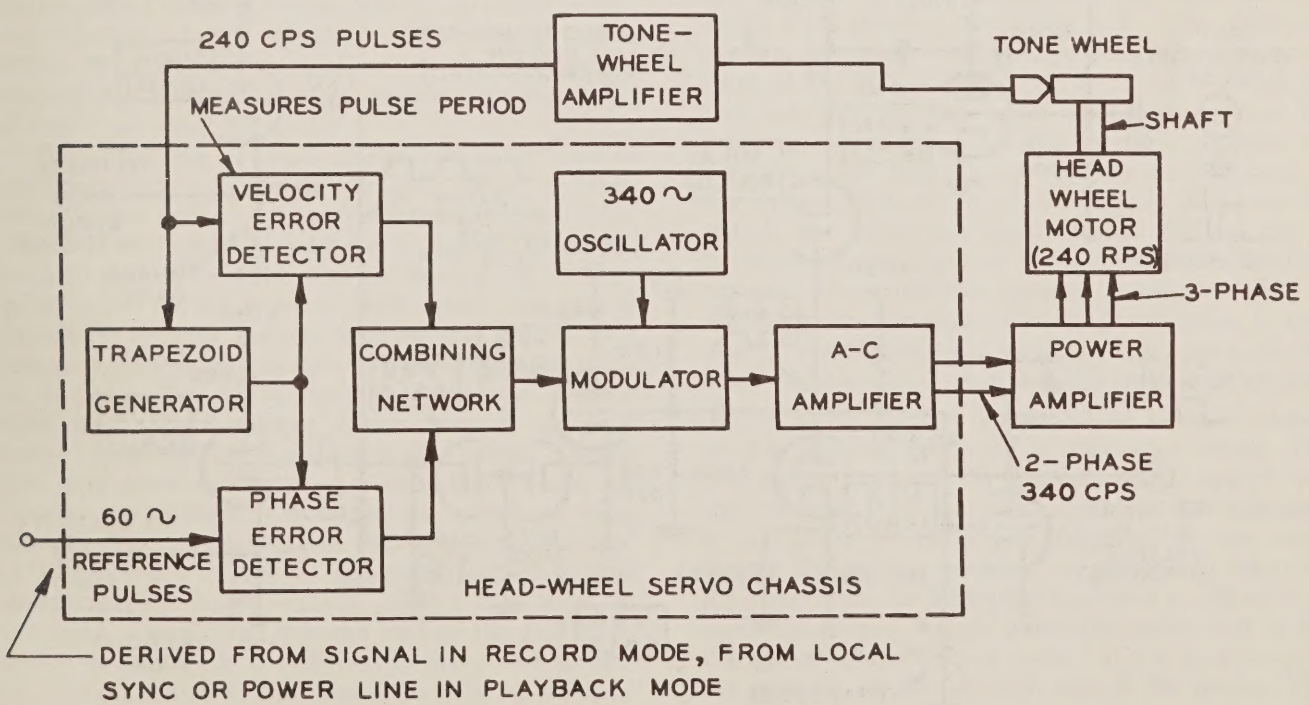

Figure HW-1. Simplified Block Diagram of Head-Wheel Servo System

sults in a cathode potential considerably more positive than ground.

The trapezoid waveform is generated across C30, the 4700-mmf capacitor at the output of V9B, as a result of the combined action of V7B and V9. When V7B is cut off during the negative half cycles of the square wave, both sides of V9 conduct through the series resistors between −150 volts and ground. Ignoring the relatively low forward impedances of the diodes, resistors R68 and R72 are effectively in parallel, yielding a net value of about 30 kilohms. This net resistance is in series with R71, and forms a voltage divider across −150 volts. The voltage across R71, which is nominally equivalent to the voltage across C30 as long as V9B is conducting, is approximately −15 volts. When the rising edge of the square-wave signal occurs, however, cathode follower V7B begins to conduct, and its cathode rises very rapidly to a voltage that is appreciably positive relative to ground. In so doing, it cuts off diode V9A, thus altering the original voltage-divider arrangement, and causing the voltage across C30 to seek a new equilibrium at about −1.5 volts (determined by the combination of R72 and R71, again ignoring the small forward impedance of V9B). The rate at which the circuit reaches this new equilibrium is determined by the time constant of R71 and C30, which is about 15.5 microseconds. (This rate of change is very fast relative to the 4167-microsecond period of the 240-cps signal.) At the beginning of the next negative half cycle, V7B is cut off, V9A is made conductive, and the voltage across R71 falls very rapidly to about −15 volts. The voltage across C30 is unable to change instantaneously, however, so diode V9B is cut off as its plate is made more negative than its cathode. The voltage across C30 then proceeds to fall toward −150 volts at a rate determined by the 330K resistor (a time constant of about 1550 microseconds). This action continues only until the cathode of V9B becomes slightly less negative than the plate, at which time V9B conducts and the output voltage again levels off at about −15 volts. The net result is that the input square wave is converted into a trapezoidal waveform with a relatively fast rise time but with a relatively slow, linear fall characteristic. The slope shown in the waveform sketch is considerably exaggerated; it is actually only about 100 microseconds out of a total period of 4167 microseconds.

A pair of cathode followers, V10A and V10B, are used to supply isolated trapezoid signals to the two error detectors. Potentiometers in the cathode circuits provide separate gain adjustments for the two servo loops. The procedure for setting these gain controls will be discussed later. In general, the gain of each loop must be set high enough to provide a tight lock-up, but not so high as to cause the system to break into oscillation.

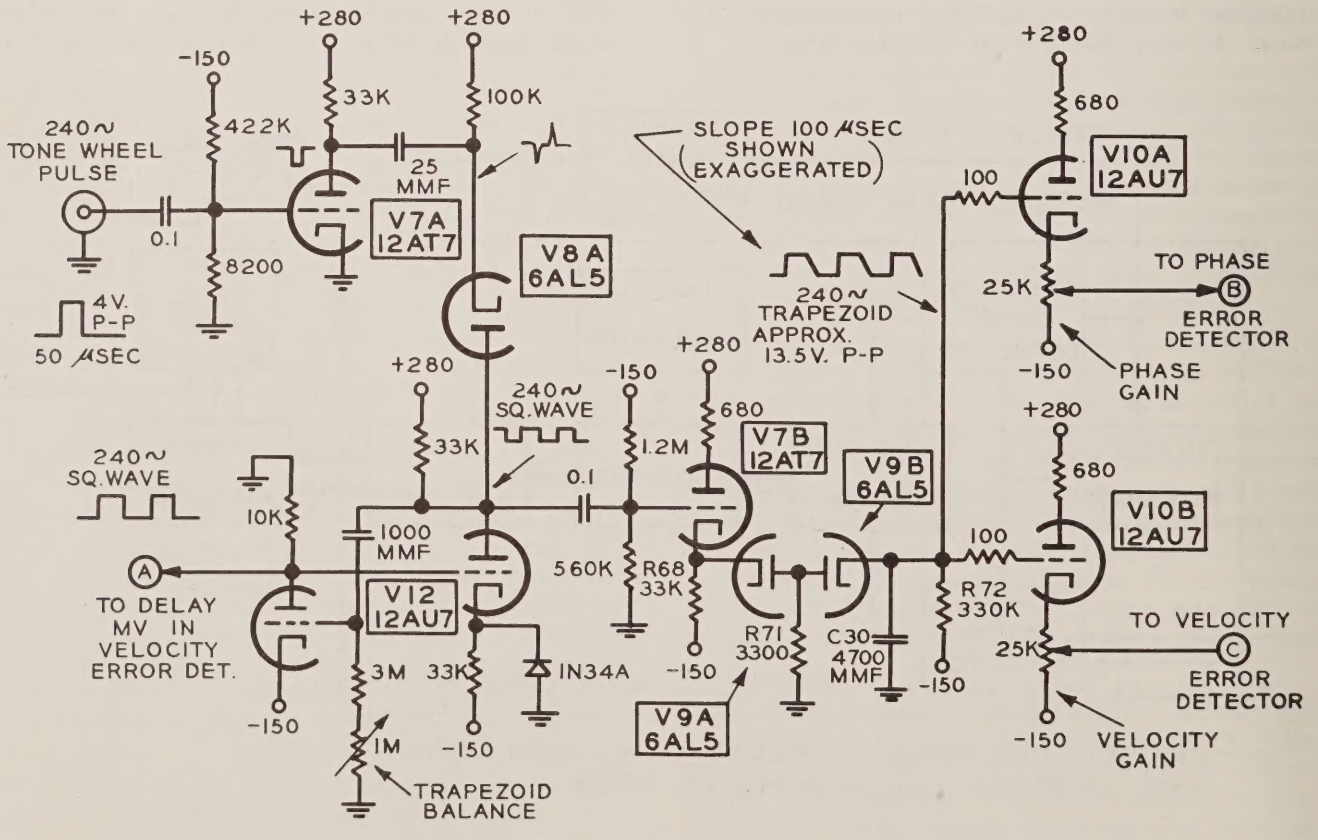

Figure HW-2. Simplified Schematic of Trapezoid Generator Section of Head-Wheel Servo

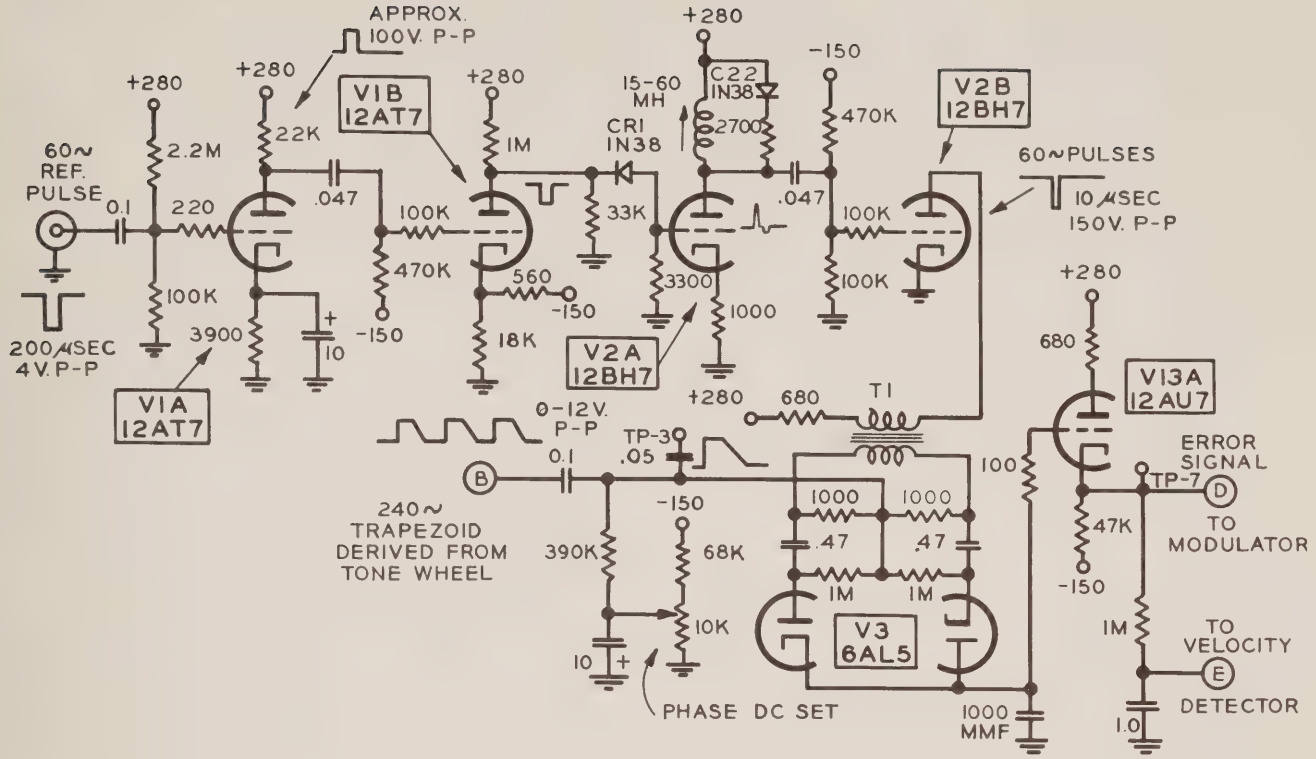

Figure HW-3. Simplified Schematic of Phase Error Detector Section of Head-Wheel Servo

PHASE ERROR DETECTOR

The circuit of the phase error detector is shown in simplified form in Figure HW-3. As noted earlier, the function of this circuit is to develop an error signal through the comparison of the tone-wheel trapezoid signal with a series of 60-cycle pulses from a stable reference generator.

The upper row of stages in this circuit are used to generate sharp sampling pulses from the input reference pulses. V1A, an amplifier with fixed bias, increases the pulse amplitude to about 100 volts, peak-to-peak. The pulse tips are leveled off by clipping action at the input of V1B; when the grid is driven far enough positive to draw grid current, the signal is sharply attenuated by the 100K resistor in series with the grid-to-cathode impedance. Diode CR1 is a second clipper which removes any disturbances along the base-line of the pulses. During the long intervals between pulses, CR1 is cut off because its cathode is returned to a voltage more positive than its anode, and the voltage at the grid of V2A remains at ground. The pulse applied to V1B causes its plate to go negative relative to ground, so the pulse is conducted through CR1 to the grid V2A, where its amplitude is sufficient to drive V2A to cut-off. The plate load for V2A consists of a diode-damped ringing coil. When the current through V2A is cut off by the leading edge of a reference pulse, the coil produces a sharp positive "spike", corresponding to the first half-cycle of an oscillation at its self-resonant frequency. The oscillation does not continue, because the negative half-cycles are suppressed by diode CR2 shunted across the coil. (The 2700-ohm resistor in series with CR2 is necessary to permit most of the tube's current to be drawn through the coil, not through the diode, during the periods between pulses.) The diode also serves to suppress the negative spike that would normally be produced at the trailing edge of the reference pulse. The rounded top of the pulse delivered by the ringing coil is flattened by grid clipping at the input of V2B, which drives a phase detector through transformer T1. As noted on the diagram, the sampling pulse is only about 10 microseconds wide, and is raised to the relatively high level of about 150 volts peak-to-peak.

The phase detector stage, V3, is a close relative of the familiar double-diode clamping circuit. The two diodes are normally non-conductive except during the very brief sampling intervals corresponding to the peaks of the pulses delivered by the transformer. During the sampling (or clamping) intervals, the charge on the 1000-mmf capacitor is adjusted to make the output voltage nominally equivalent to the voltage occurring at that instant at the center-tap of the network on the opposite side of the diodes. The voltage across the 1000-mmf capacitor remains reasonably constant between clamping intervals, because when the diodes are open the charge on the capacitor

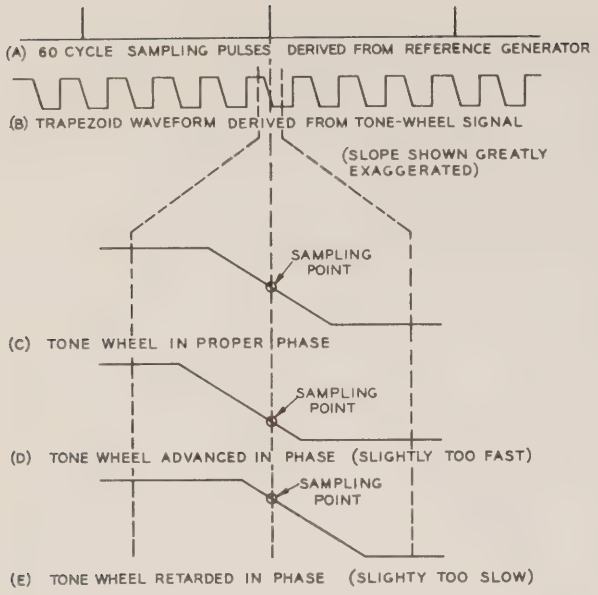
(A) 60 CYCLE SAMPLING PULSES DERIVED FROM REFERENCE GENERATOR
(B) TRAPEZOID WAVEFORM DERIVED FROM TONE-WHEEL SIGNAL
(SLOPE SHOWN GREATLY EXAGGERATED)
SAMPLING POINT
(C) TONE WHEEL IN PROPER PHASE
SAMPLING POINT
(D) TONE WHEEL ADVANCED IN PHASE (SLIGHTLY TOO FAST)
SAMPLING POINT
(E) TONE WHEEL RETARDED IN PHASE (SLIGHTY TOO SLOW)

Figure HW-4. Waveform Sketches Illustrating the Operation of the Phase Error Detector

can be altered only through high-impedance leakage paths. The signal applied to the center-tap of the clamper network is the 240-cps trapezoid waveform derived from the tone-wheel signal. Provision is made for adding a d-c component to the waveform so as to adjust the absolute voltage at the midpoint of the slope on the trapezoid to a reasonable level for the following modulator.

The operation of the phase detector circuit is illustrated by the waveform sketches in Figure HW-4. Only every fourth cycle of the trapezoid waveform is actually used, because the reference pulses occur only at a 60 cps rate. When the head-wheel is rotating at the proper speed, the sampling (or clamping) instant should occur exactly at the midpoint of the slope on the trapezoid waveform, as shown at (C). If the motor tends to run slightly too fast, the apparent phase of the trapezoid will be advanced relative to the reference pulses, so the sampling will occur at a lower point on the waveform, and the error signal output will be reduced. This reduced-level error signal will, through the modulator circuit to be discussed presently, reduce the power supplied to the motor so as to restore it to the proper speed. In similar fashion, a tendency for the motor to run too slow will cause the error signal to increase in voltage because of the retarded phase of the trapezoid

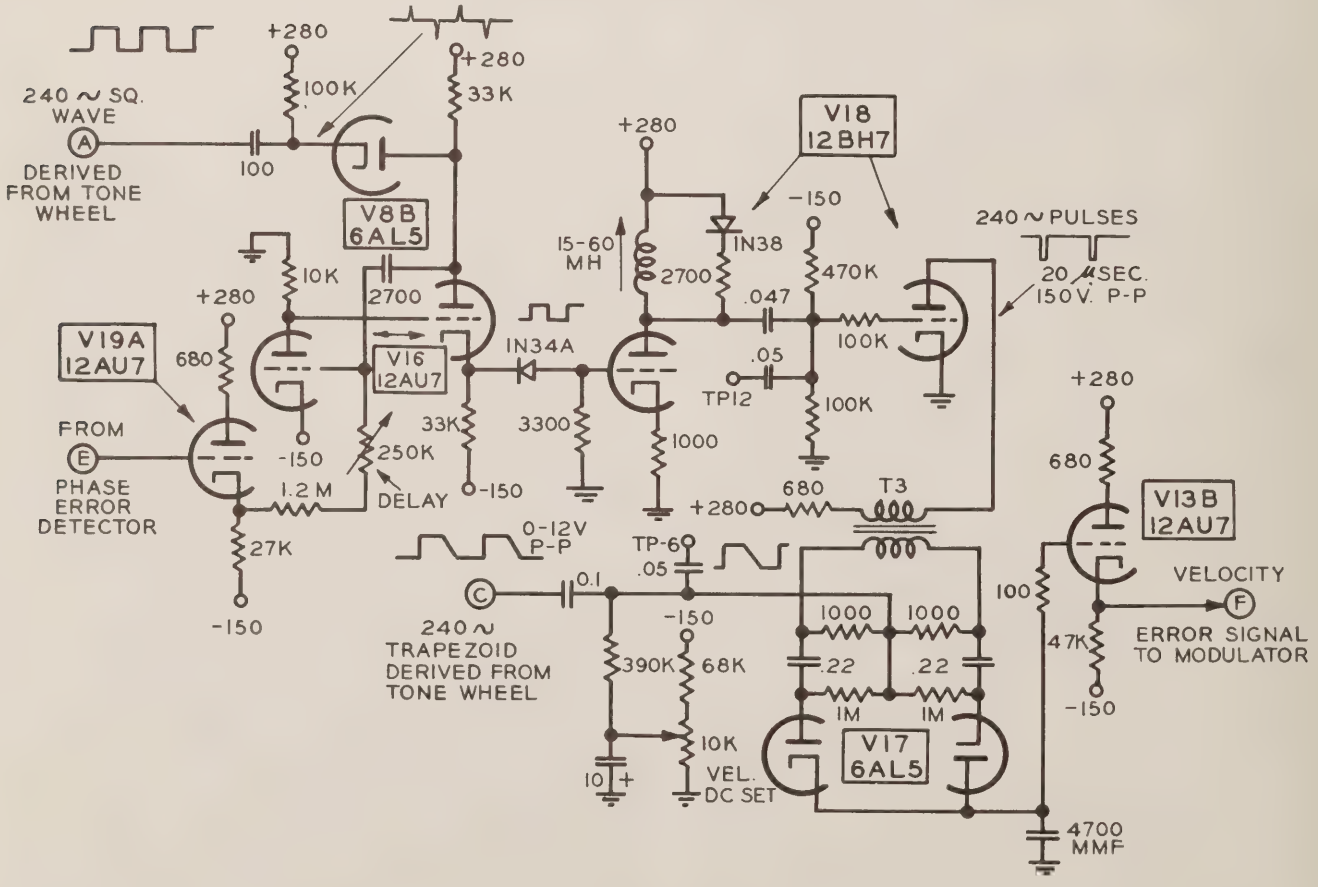

Figure HW-5. Simplified Schematic of Velocity Error Detector Section of Head-Wheel Servo

signal, and the increased error signal will increase the power supplied to the motor so as to bring it back up to speed.

The final stage shown in Figure HW-3, V13A, is a cathode follower which supplies a reasonably low-impedance drive for the modulator. A second output from V13A is directed to the velocity error detector through an RC integration network. The purpose of this output is to modify the operation of the velocity error detector so that it does not conflict with the phase error detector.

VELOCITY ERROR DETECTOR

The velocity error detector, shown in slightly simplified form in Figure HW-5, is quite similar to the phase error detector, but the sampling pulses which operate the clamp-type detector are derived from a 240-cps square wave instead of from the 60-cps reference pulses. The input square wave from V12 is differentiated, and the negative-going "pips" are coupled through diode V8B to trigger V16, a stabilized multivibrator. Sharp sampling pulses are derived from the falling edges of the pulses produced at the cathode of V16B by the ringing coil in the plate circuit of the left side of V18. The functions performed by the two sections of V18 are identical to those previously discussed for V2A and V2B in Figure HW-3. Phase detector V17 is also identical to stage V3 in Figure HW-3, except that a 4700-mmf output capacitor is used instead of a 1000-mmf capacitor because four times as many pulses are available to replenish the charge on the capacitor. As in the case of the phase error detector, a cathode follower, V13B, is used at the output to provide a driving point of reasonably low impedance for the modulator.

The operation of the velocity error detector is best explained with the aid of the waveform sketches in Figure HW-6. The 240-cps sampling pulses used in the velocity error detector are actually delayed nominally one full period by virtue of the fact that two multivibrators are triggered in series to produce them. The net result is that the time interval between each sampling pulse and the leading edge of the *preceding* tone-wheel pulse is determined only by electrical time constants, and is therefore independent of the tone-wheel speed. The width of the pulse produced by the first multivibrator is adjusted to make the square wave as symmetrical as possible, and the width of the pulses produced by the second are adjusted to make their trailing edges coincide with the mid-points of the slopes in the trapezoid waveform when the head-wheel is operating at exactly 240 rps. Once these adjustments are made, the relative phase of the sampling pulses and the trapezoid signal will vary slightly if the head-wheel is not running at the proper speed. If the head-wheel runs slightly too fast, for example, the period of the trapezoid waveform is shortened slightly, causing the sampling point in the detector to slide down the waveform, thus generating an appropriate error signal. In effect, the detector is actually measuring

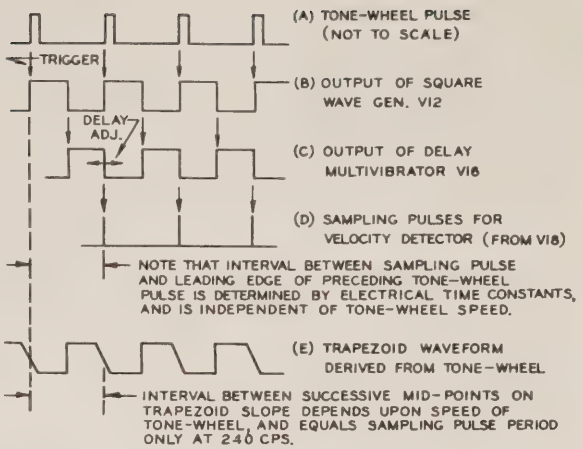
(A) TONE-WHEEL PULSE (NOT TO SCALE)
TRIGGER
(B) OUTPUT OF SQUARE WAVE GEN. V12
DELAY ADJ.
(C) OUTPUT OF DELAY MULTIVIBRATOR V16
(D) SAMPLING PULSES FOR VELOCITY DETECTOR (FROM V18)
NOTE THAT INTERVAL BETWEEN SAMPLING PULSE AND LEADING EDGE OF PRECEDING TONE-WHEEL PULSE IS DETERMINED BY ELECTRICAL TIME CONSTANTS, AND IS INDEPENDENT OF TONE-WHEEL SPEED.
(E) TRAPEZOID WAVEFORM DERIVED FROM TONE-WHEEL
INTERVAL BETWEEN SUCCESSIVE MID-POINTS ON TRAPEZOID SLOPE DEPENDS UPON SPEED OF TONE-WHEEL, AND EQUALS SAMPLING PULSE PERIOD ONLY AT 240 CPS.

Figure HW-6. Waveform Sketches Illustrating the Operation of the Velocity Error Detector

the period between successive tone-wheel pulses. The pull-in range of this detector is considerably greater than that of the phase error detector, and it develops a useful error signal as soon as tone-wheel pulses first appear when the machine is started up (pulses appear at about 60 rps).

Cathode follower V19A, coupled to the pulse-width-determining time constant in multivibrator V16, is the means by which the output of the phase error detector modifies the operation of the velocity error detector to prevent the two circuits from delivering contradictory information to the modulator. The operation of this circuit is best explained by considering what happens if the servo system is subject to a sudden transient disturbance. Suppose, for example, that the head-wheel motor is operating in the record mode at exactly the right speed, but that it suddenly finds itself in improper phase because of a sudden switch to a different composite picture signal at the input. The reference pulses may still be produced at exactly the same 60-cps rate, but a time discontinuity in the input signal could cause the sampling pulses derived from the reference pulses to jump completely off the slope of the trapezoidal waveform, and sample either the positive or negative flat portion. Let's suppose that the sampling occurs during the positive flat portion, in which case the phase error detector generates its maximum error voltage in the direction implying that the motor should speed up slightly to correct the phase discontinuity. Although the motor is actually running at the proper speed (and therefore producing no error signal from the velocity error detector), it must accelerate momentarily to correct for the phase discrepancy. When this acceleration occurs, however, the velocity error detector, if left unmodified, would produce an error signal in such a direction as to counteract the desired acceleration. To prevent this conflict, the positive error signal from the phase detector is applied through cathode follower V19A to shorten by a slight amount the pulse period of multivibrator V16. This effectively shortens the

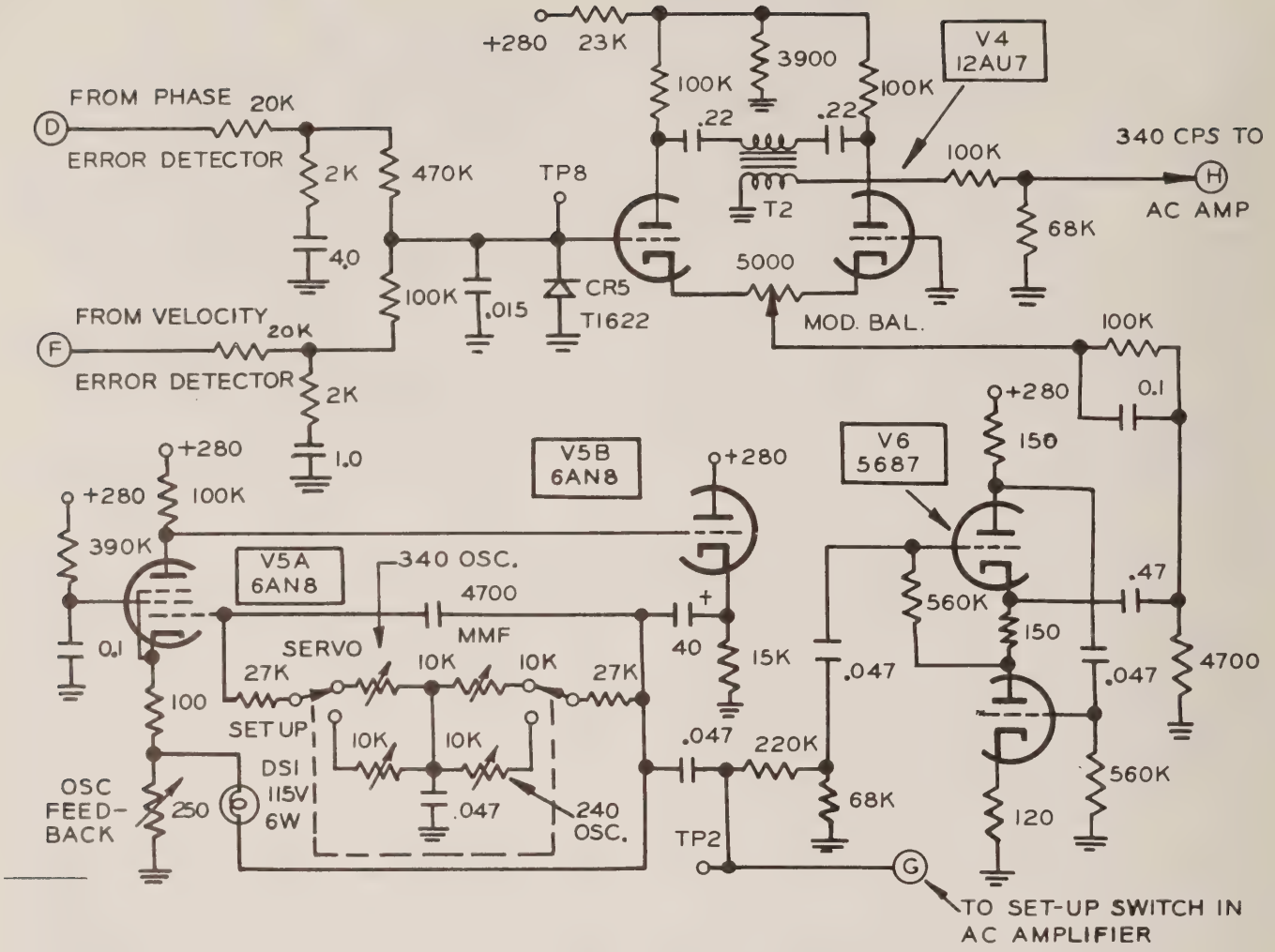

Figure HW-7. Simplified Schematic of Oscillator and Modulator Section of Head-Wheel Servo

"yardstick" against which the velocity error detector measures the pulse periods, and thus prevents the generation of the unwanted velocity error signal. In normal operation, when the phase error is seldom so great as to cause the sampling pulses to leave the trapezoid slope, the cross-coupling of the detectors through V19A results in increased gain for the servo system. That is, a slight increase in the error voltage as a result of a minor phase error will cause the velocity error detector to develop a slight positive voltage also. The integrating network between V13A (Figure HW-3) and V19A prevents the velocity error detector from following the slight high-frequency variations in the phase error detector.

OSCILLATOR AND MODULATOR

Figure HW-7 shows the oscillator and modulator sections of the head-wheel servo. The oscillator, V5, is of the bridged-T type, and is stabilized by a non-linear impedance. There are actually two feedback connections in this oscillator. Positive feedback, tending to cause oscillation, is provided through lamp DS1 from the cathode of V5B to the cathode of V5A. Degenerative feedback, tending to prevent oscillation, is provided through an adjustable bridged-T network between the cathode of V5B and the grid of V5A. At the null frequency of the bridged-T network, the degenerative feedback is effectively removed, permitting oscillation at only that frequency. Two separate controls to set the null frequency are provided on a switchable basis. One of these is adjusted to 240 cps for set-up and test purposes, and the other is adjusted to 340 cps for normal servo operation. The amplitude of oscillation is regulated by the non-linear impedance of lamp DS1. If the amplitude of oscillation tends to increase, the greater current passed through the lamp causes its resistance to go up, thus reducing the positive feedback and limiting the amplitude to a nearly constant value. The oscillator must operate at a relatively high level to achieve this stabilization, so a voltage divider consisting of 220K and 68K resistors is used to reduce the amplitude of the output signal before application to the buffer amplifier, V6. V6 is a series amplifier operated as a cathode follower to provide a low-impedance driving point for the modulator. The buffer and modulator are by-passed when the 240-cps signal is used for set-up purposes – the terminal marked "G" leads

directly to the second stage in the output amplifier section, to be discussed presently.

The modulator, V4, uses a pair of triodes in a balanced circuit. If the voltages on the two grids were exactly equal, there would theoretically be no output, since the 340-cps "carrier" signal is applied equally to the two cathodes, and there would be no voltage difference across the primary of the output transformer. The grid voltages are not equal, however, because one side is grounded and the other is supplied with the combined outputs of the two error detectors. Thus there is a 340-cps signal at the output, and its amplitude varies in accordance with the combined error signal. The error signals are combined through low-pass RC filters and isolation resistors. The impedances in this combining network have been chosen to adjust both the frequency response and phase characteristics of the respective servo loops for optimum performance. Diode CR5 prevents the voltage on the grid of the left side of V4 from going significantly negative relative to ground – the voltage at this point should always be positive, because the motor always runs in the same direction.

A-C AMPLIFIER SECTION

The final stages on the servo chassis, shown in Figure HW-8, are a-c voltage amplifiers which increase the amplitude of the 340-cps signal to a level suitable for transmission to the main power amplifiers, located on separate chassis. V11 and V14 are identical feedback-pair voltage amplifiers, with negative feedback between the plate of the second stage and the cathode of the first. Note that the off-on relay stops the head-wheel motor by interrupting the signal at the input to the second of these amplifiers, V14. There is also provision for substituting a 240-cps signal for the normal servo output for set-up purposes – the switch shown on this diagram is mechanically coupled to the switch shown in Figure HW-7 which changes the oscillator frequency. In the "set-up" condition, the motor is operated in synchronism at 240 revolutions per second.

The output cathode follower, V15A, has two phase-shifting networks tied to its cathode. One of these advances the phase and the other retards it. A control on the upper network permits adjustment of the phase difference to exactly 90 degrees at 340 cps. Separate gain controls are provided for the two outputs. For proper operation of the Scott-connected transformers at the output of the two power amplifiers, the voltage through the 90° branch should be approximately 0.866 of the voltage through the zero-phase branch. As noted on the diagram, the voltage level on the zero-phase line is about 1.5 volts when the servo system is operating under a normal load.

POWER AMPLIFIERS

The two quadrature signals at the output of the servo chassis are raised to the power level necessary to drive the head-wheel motor by a pair of 70-watt audio amplifiers. A simplified schematic for one of these amplifiers is shown in Figure HW-9. (Two of

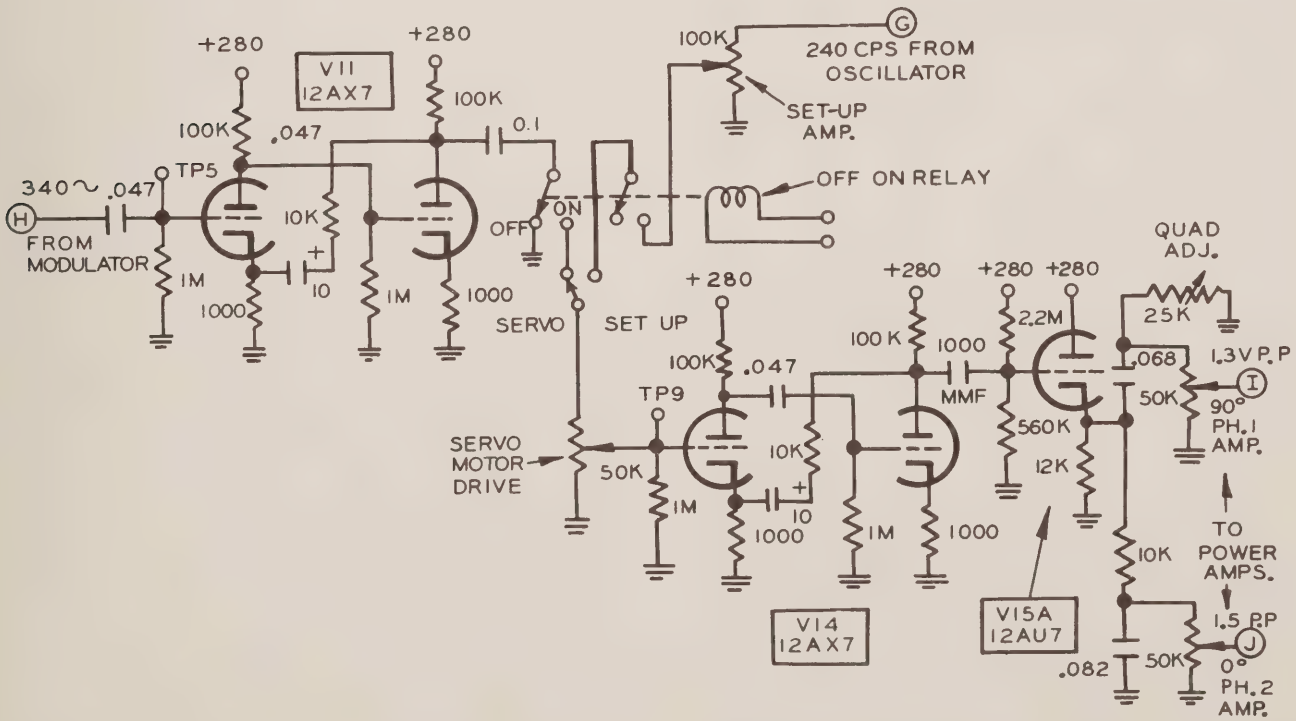

Figure HW-8. Simplified Schematic of A-C Amplifier Section of Head-Wheel Servo

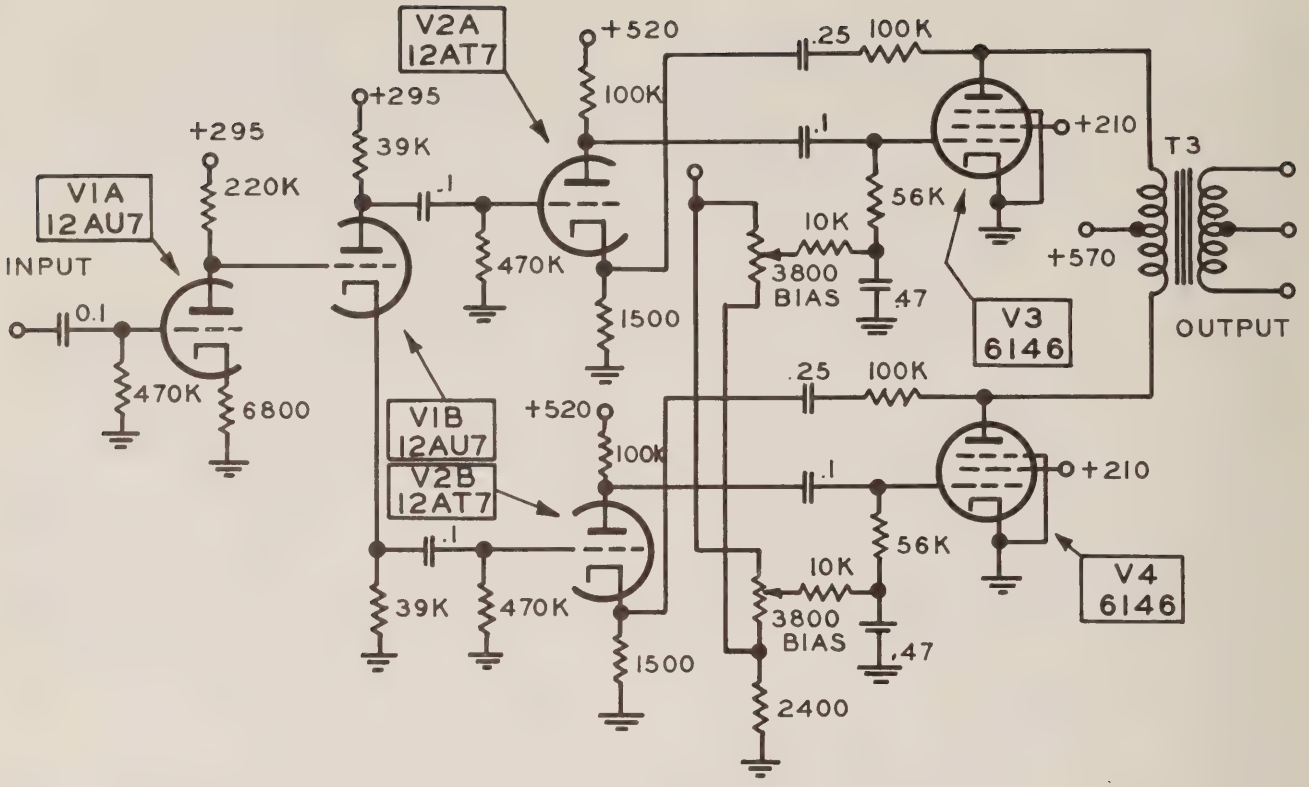

Figure HW-9. Simplified Schematic of 70-Watt Power Amplifier Used in Both Head-Wheel and Capstan Servo Systems

these same amplifiers are also used in the capstan servo system, identical except for slightly different connections for the secondary windings of the output transformers.)

The first stage, V1A, is a voltage amplifier stabilized by the degeneration resulting from the unbypassed cathode resistor. V1B is a phase splitter, which delivers out-of-phase signals to V2A and V2B. V2A and V3 form a feedback pair, with a negative feedback path for stabilization connected between the plate of V3 and the cathode of V2A. V2B and V4 form a similar pair. Transformer T3 is driven in push-pull fashion from the plates of V3 and V4. The only controls on the power amplifier chassis are an off-on switch and two bias adjustments to set the operating currents in the output tubes.

The conversion from 2-phase to 3-phase power by the use of the so-called Scott transformer connection is illustrated by Figure HW-10. As noted earlier, the voltage of the output circuit operating at the 90-degree phase position must be set at 86.6% of the voltage in the reference phase circuit. When one side of the 90° output transformer is connected to the center tap of the 0° transformer, as shown at the left, the voltages between the three output leads are combined vectorially to produce the three balanced voltages shown in the vector diagram at the right.

SET-UP AND OPERATING ADJUSTMENTS

There are approximately 12 different types of controls used in the head-wheel servo system, exclusive of those in the reference generator and tone-wheel amplifier. This technical description of the head-wheel servo system will be concluded by a brief discussion of these controls and the proper procedures for adjusting them. In a number of cases, adherence to a proper procedure is quite vital, because several of the controls are effectively in series and adjustment in the wrong sequence could result in improper operation.

Several of the controls are quite routine and relatively independent. For example, the BIAS adjustments in the output amplifiers are used only to set the operating currents in the output tubes at 28 milliamperes, as measured with a plug-in meter. This adjustment should be made with no signal present, a condition which can be achieved by pulling the plug from J5, the output jack on the servo chassis. (The plug should be left out while making the adjustments described in the next two paragraphs.) The MODULATOR BALANCE control shown in Figure HW-7 can readily be adjusted by shorting the input grid (TP8) and adjusting for minimum output as monitored at TP5 (Figure HW-8). The

PHASE DC SET control (Figure HW-3) is adjusted to give zero volts d-c at the cathode of V13A (TP7).

The two frequency controls associated with the oscillator may be set either by direct comparison with a calibrated audio oscillator, or by comparison with the 60-cycle component of a TV signal. A convenient way to set the 240 OSCILLATOR adjustment by the latter technique is to look at TP2 (the oscillator output, Figure HW-7) with an oscilloscope whose horizontal sweep is triggered by vertical drive. The adjustment is correct when the oscillator produces four cycles in each 60-cycle period. It is somewhat more difficult to set the 340 OSCILLATOR adjustment by this technique, because 340 cps is not a harmonic of 60 cycles. A reasonably close adjustment can be made, however, by noting the control positions giving five and six cycles for each 60-cycle period. These are the points corresponding to 300 and 360 cps, respectively, and the proper setting is two-thirds of the way from the fifth to the sixth harmonic. Fortunately, the precise setting of this oscillator is not too vital, provided the frequency is not changed indiscriminately after other adjustments are completed. The OSCILLATOR FEEDBACK control is adjusted to give a peak-to-peak level of 5 volts at TP2 — this is the proper level for optimum stabilizing effect in the nonlinear impedance, DS1.

A proper operating level for the modulator is obtained by adjustment of the SERVO MOTOR DRIVE control, shown in Figure HW-8. To set this control, the voltage at the active grid of the modulator (TP8, Figure HW-7) should first be set at 0.8 volts d-c with the VELOCITY DC SET control, Figure HW-5 (this is *not* the final setting for this control). The SERVO MOTOR DRIVE control should then be set to give a 340-cps signal of 1.0 volt peak-to-peak at TP9 (connected to the movable arm of the control). The PHASE 1 AMPLITUDE and PHASE 2 AMPLITUDE controls (Figure HW-8) should be near their maximum settings — these controls are used only to balance the two phases by a procedure to be discussed presently. The QUADRATURE ADJUSTMENT control should be set while the oscillator is running at 340 cps and the grid voltage on the modulator remains at 0.8 volts, as above. The desired 90-degree relationship between the two phases may be checked by the use of a dual-trace oscilloscope or by the use of a single-trace oscilloscope with its sweep triggered externally by just one of the two phases. Once these adjustments are completed, the VELOCITY DC SET control should be adjusted to give +2 volts d-c at the modulator grid, TP8. Except for the possibility of a slight touch-up later, this is the final setting of the VELOCITY DC SET control, and it is important that it be made with no tone-wheel pulses present. It is set substantially above zero so as to provide an appropriate start-up voltage for the motor.

The motor must be running for the remaining adjustments, so the output plug should be inserted in jack J5 at this point in the procedure. With the SERVO/SET-UP switch in the SET-UP position, the SET-UP AMP. control should be advanced from zero until the voltage across the motor windings, as indicated by the built-in meter on the servo chassis, is approximately 60 volts. The PHASE 1 AMPLI-

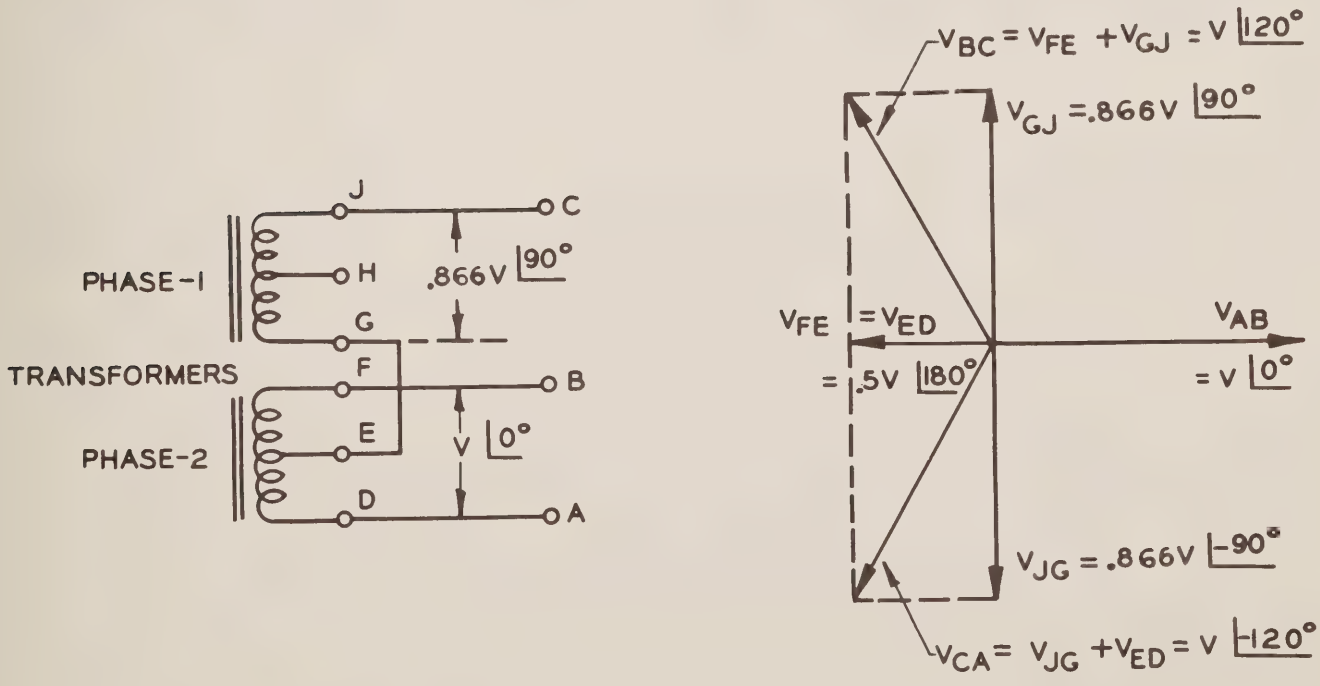

Figure HW-10. Conversion from 2-Phase to 3-Phase Power by Scott-Connected Transformers

TUDE and PHASE 2 AMPLITUDE controls should then be adjusted to make the voltages across all three phases equal within ±5 volts; these controls should remain near their maximum settings. The motor should now be running synchronously at 240 rps; this condition can be checked by determining whether the tone-wheel pulses are synchronous with the 240-cps oscillator output.

Preliminary adjustment of the velocity error detector should be made with the motor running in the 240-cps synchronous condition and with normal tone-wheel pulses present. The VELOCITY GAIN control (Figure HW-2) is adjusted to give a 12-volt peak-to-peak signal at the input to the phase detector used to develop the velocity error signal (TP6, Figure HW-5). The TRAPEZOID BALANCE control is then adjusted to make the slope in the trapezoid waveform occur exactly half way between two straight edges, as monitored with an oscilloscope at TP6. This adjustment affects the timing of the sampling pulses in the velocity error detector, so it should not be touched once it is properly set. The DELAY control (Figure HW-5) should then be set to make the sampling "pip" (visible in the waveform at TP6) occur at the midpoint of the slope on the trapezoid. To make sure that the cross-coupling from the phase error detector through V19A does not influence this adjustment, it is desirable to short out the phase error detector by a jumper from TP7 to ground while this preliminary DELAY adjustment is being made.

The final adjustments in the error detector circuits must be made with the SERVO/SET-UP switch in the SERVO position. An oscilloscope should be connected through a low-capacity probe to TP3, the center-tap of the clamp in the phase error detector (Figure HW-3). The PHASE GAIN control should be advanced to give about a 2.0-volt peak-to-peak trapezoid signal at TP3, and the DELAY control (Figure HW-5) should be touched up to cause the 60-cps sampling pulses to "lock up" at the center of the slope on every 4th cycle of the trapezoid (a "pip" showing the location of the sampling pulse is visible in the waveform at TP3). Once lock-up is achieved, the PHASE GAIN control (Figure HW-2) should be advanced slowly until the position of the spike on the slope begins to waver, indicating instability. The proper operating point is just below the point where instability begins, corresponding to the maximum permissible gain in the servo system. The normal peak-to-peak voltage at TP3 under these conditions is about 4 volts.

As a final check, the motor should be stopped and then re-started in the SERVO position of the set-up switch. The start-up voltage applied to the motor should be approximately 65 volts, as measured with the built-in meter. If it is not about this value, either the VELOCITY DC SET or the SERVO MOTOR DRIVE control should be touched up slightly to make it so. It may also be necessary to re-touch the PHASE 1 AMPLITUDE and PHASE 2 AMPLITUDE controls to balance the voltages across the three phases while the motor is running with 340-cps power. If much change is required, the error detector adjustments should be re-checked to make sure the circuits are operating properly. The most critical adjustment in the entire servo system is the DELAY control, which sets the precise operating points for both error detectors through its influence on the "yardstick" used for measuring the motor's velocity.

CAPSTAN SERVO SYSTEM

OBJECTIVES

The purpose of the capstan servo system is to control the capstan motor, which in turn controls the speed with which tape is pulled through the machine. Actually, the capstan is controlled by a servo system only in the playback mode. In the record mode, the capstan motor is simply driven by 60-cycle power at the same frequency as the power line, while a control track on the tape makes a continuous record of the speed of the head-wheel motor. During playback, the capstan is controlled by the true servo system shown in simplified form in Figure CS-1. The speed of the tape is controlled by a continuous comparison of the 240-cps signal from the control track with a 240-cps signal derived from the tone wheel on the head-wheel motor. This type of servo control is necessary to assure that the video heads pass exactly over the recorded video tracks on the tape; without such control, the relative positions of the heads could tend to drift along the length of the tape, frequently bridging two adjacent recorded tracks instead of remaining over single tracks. Because the phase stability requirements are not too severe, it is practical to operate the capstan motor in a synchronous mode and to use a relatively simple type of servo system in which the error detector frequency-modulates a 60-cps oscillator whose output is amplified to drive the motor.

The capstan servo chassis also includes the circuits for recording, monitoring, and playing back the control track. These circuits will also be described in this article, since they are closely related to the capstan servo system.

OVERALL BLOCK DIAGRAM OF SERVO CHASSIS

A block diagram of the circuits included on the capstan servo chassis is presented in Figure CS-2. The several switching functions which alter the signal paths for the playback and record modes are actually performed by relays which are electrically connected to the main RECORD and PLAY buttons on the tape transport control panel. In the record mode, the signal applied to the motor drive circuits is picked up directly from the 60-cycle power line. Two phases, 90 degrees apart, are provided by phase shifting networks at the output of the servo chassis. The two phases are then amplified separately in 70-watt amplifiers (not shown) and applied directly to the two-phase capstan motor.

The tone-wheel signal is used in the record mode to develop the basic signal for the control track. The 240-cps input square wave is converted to a sine wave by a filter, combined with a field identification pulse, and applied to the control track head through a suitable recording amplifier. The field pulse is generated in the Reference Generator, and is used primarily to identify the proper cutting point in tape splicing operations. Provision is made for monitoring the current through the control track head both with

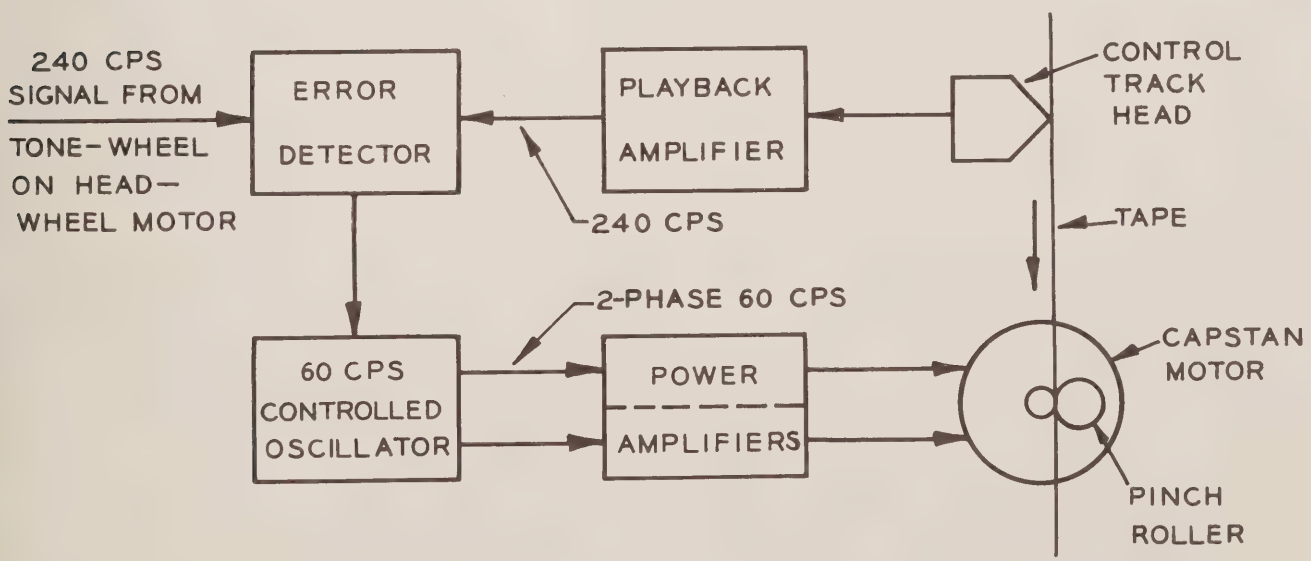

Figure CS-1. Greatly Simplified Block Diagram of Capstan Servo Loop (Used in Playback Mode Only)

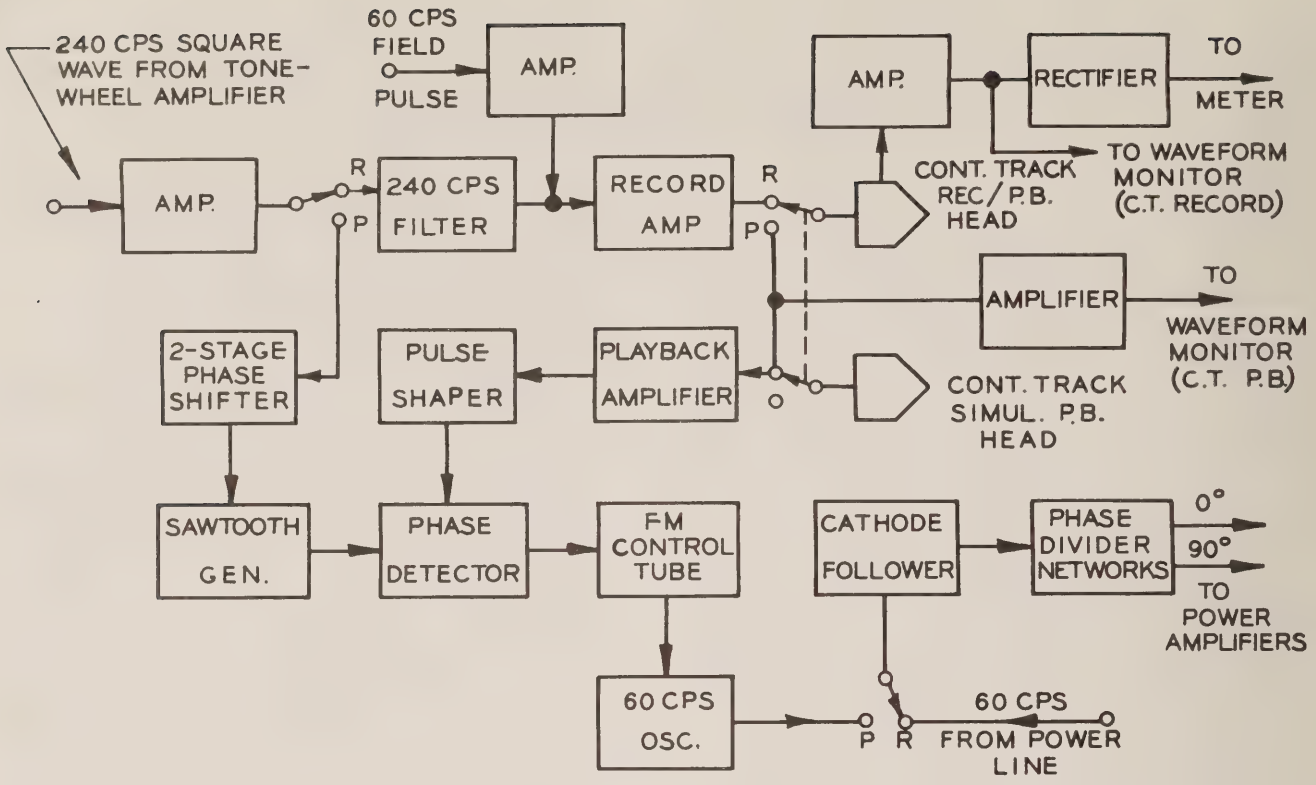

Figure CS-2. Simplified Block Diagram of Circuits on Capstan Servo Chassis

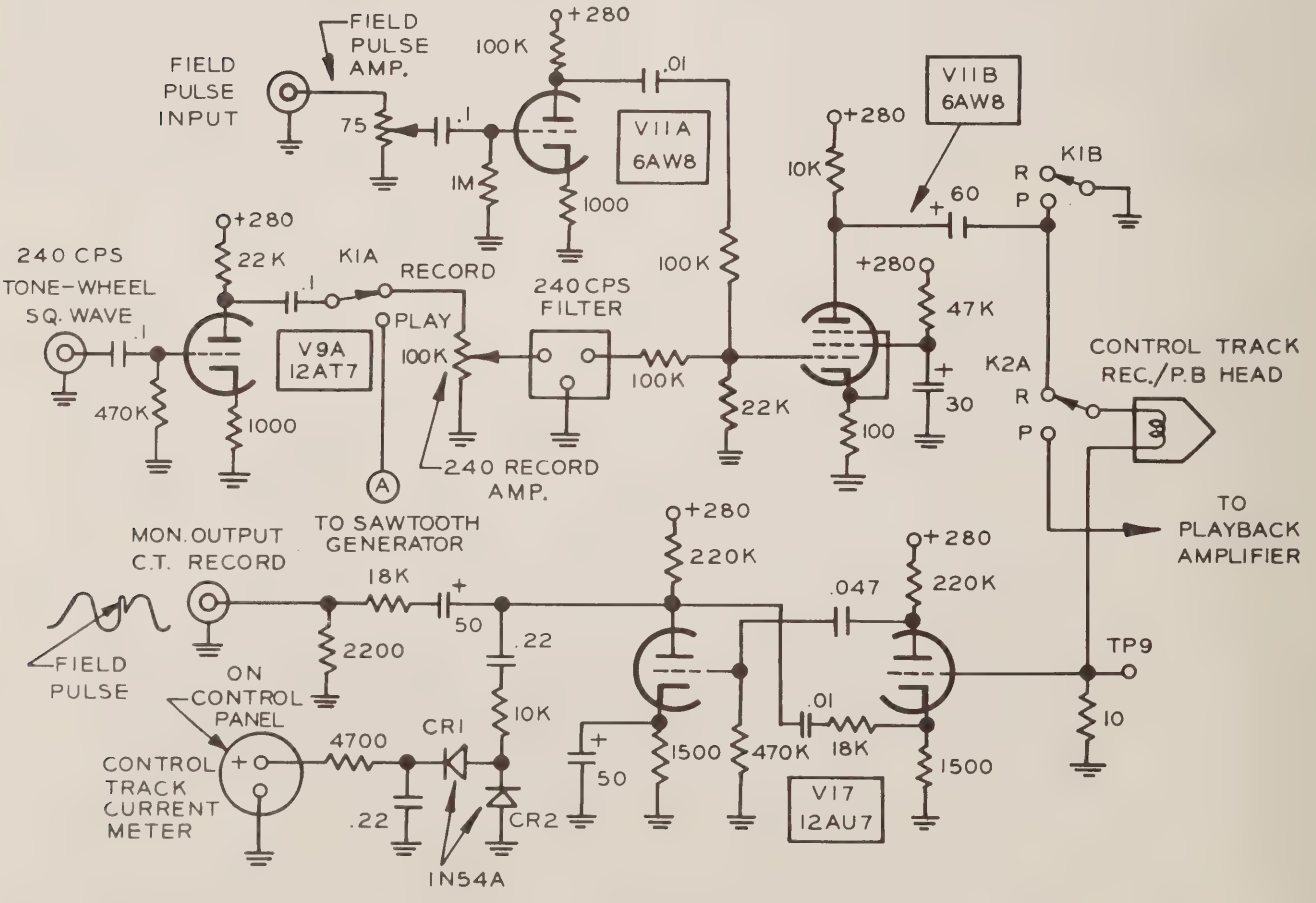

Figure CS-3. Control Track Recording Circuits (Part of Capstan Servo Chassis)

a waveform monitor and with a meter mounted on the main control panel. To make doubly sure that the control track is recorded properly, a simultaneous playback head is mounted on the tape transport panel and connected through an amplifier to the waveform monitor. The simultaneous playback head is used only in the record mode; for playing back a complete recording, the same head used for recording the control track is used for playback so as to preserve the original time relationships in the signals, and to reduce to a minimum the length of tape between the video head wheel and the control track head.

In the playback mode, the 240-cps sine wave recovered from the control track is converted into a sharp sampling pulse, and compared in a phase detector with a sawtooth generated from the tone-wheel signal. The tone-wheel signal is passed through a wide-range phase shifter which provides a manual adjustment for centering any of the four video heads over any desired track in the recorded tape. The output of the phase detector is applied to a control tube which modifies the frequency of a 60-cps oscillator just enough to maintain the tape motion at the proper speed.

Circuit details will now be explained with the aid of a series of simplified schematic diagrams, similar to those presented for the head-wheel servo.

CONTROL TRACK RECORDING CIRCUITS

The circuits shown in Figure CS-3 are used for recording the control track. The 240-cps tone-wheel square wave is amplified in V9A, converted to a sine wave by a "packaged" 240-cps filter, and mixed with the field pulse signal by a resistance mixing network at the grid of V11B. Note that both V9A and V11A (the field pulse amplifier) are stabilized by cathode degeneration. V11B is the driving amplifier for the control track recording head. A 10-ohm current-sampling resistor is connected in series with the control track head, and the signal across this resistor is amplified in V17, a feedback-pair amplifier. The output of V17 is directed both to the waveform monitor (through an 18K isolating resistor) and to a rectifier which drives the control track current meter on the main control panel.

CONTROL TRACK PLAYBACK AMPLIFIERS

Figure CS-4 shows the playback amplifiers for the control track. In the record mode, the simultaneous

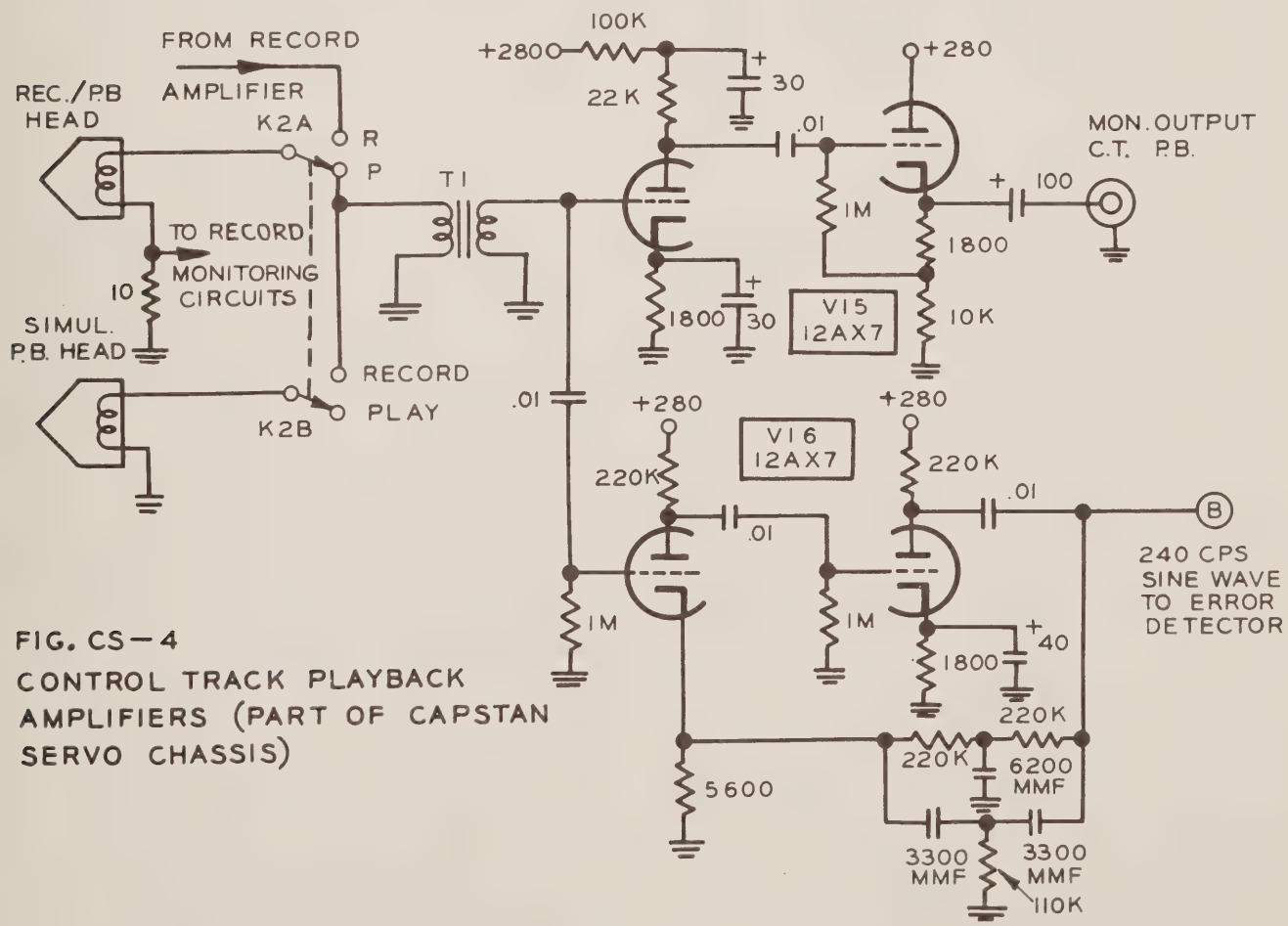

FIG. CS—4
CONTROL TRACK PLAYBACK AMPLIFIERS (PART OF CAPSTAN SERVO CHASSIS)

Figure CS-4. Control Track Playback Amplifiers (Part of Capstan Servo Chassis)

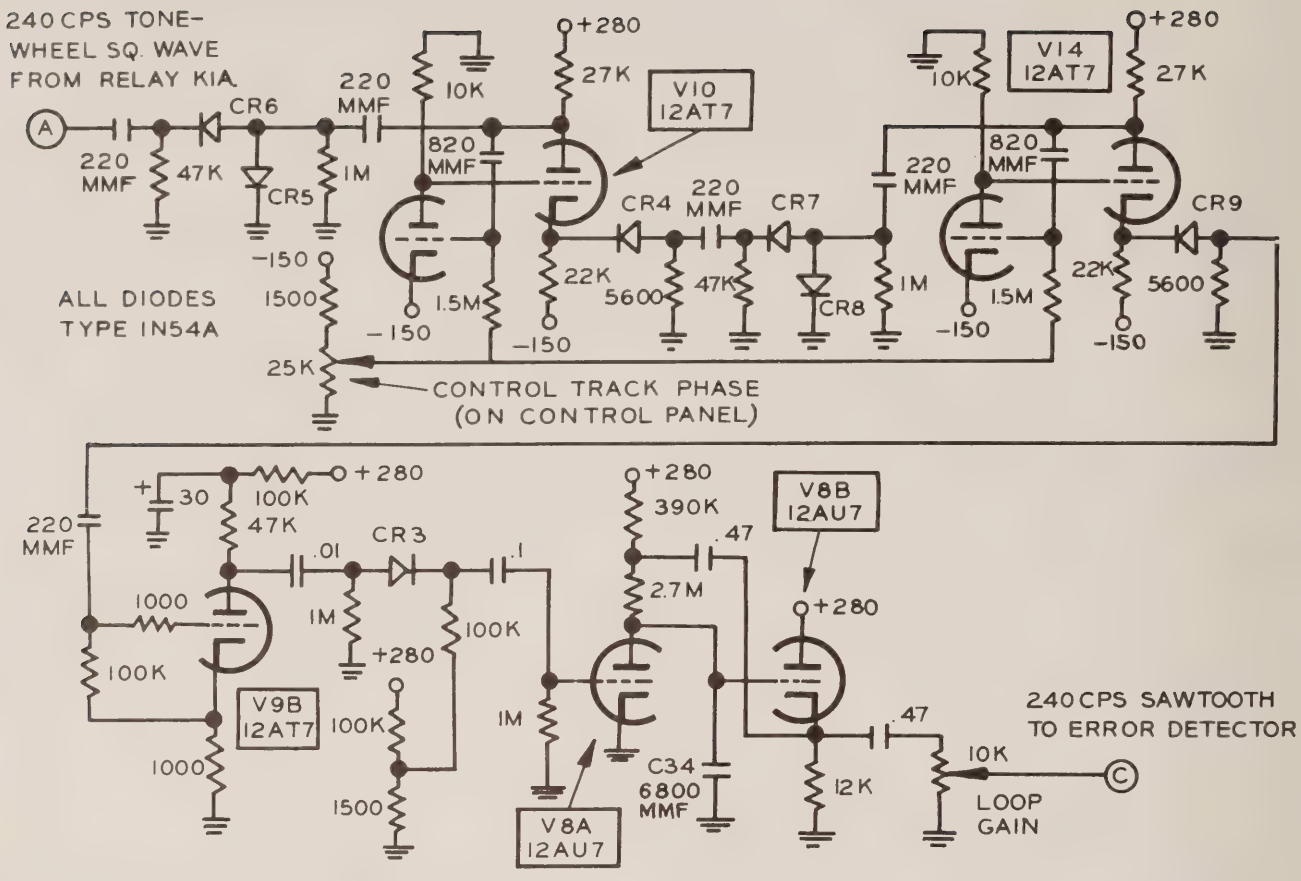

Figure CS-5. 240 Cps Phase Shifter and Sawtooth Generator Circuits for Capstan Servo

playback head is connected to the input transformer (T1), while in the playback mode the main control track record/playback head is so connected. Separate amplifiers are used to drive the waveform monitor and the error detector. The monitor amplifier, V15, consists of a voltage-gain stage followed by a cathode follower. V16 is a feedback-pair amplifier in which the feedback path consists of a twin-T network. This network presents a high impedance at 240 cps, so the negative feedback at this frequency is relatively low and the gain is correspondingly high. At higher frequencies, the feedback is considerably greater, and the gain is greatly reduced. The net result is that the signal delivered to the following stages is a reasonably pure sine wave.

240-CPS PHASE SHIFTER AND SAWTOOTH GENERATOR CIRCUITS

Before the 240-cps signal from the control track is compared with the 240-cps signal from the tone wheel attached to the head motor, the latter signal is adjusted in phase and converted to a sawtooth waveform by the circuitry shown in Figure CS-5. An adjustable phase shift of slightly more than one full cycle at 240 cps is required to make it possible to center any of the four video heads over any given recorded track on the tape. (Such flexibility in track-head combinations makes it possible to adjust the machine for nearly uniform signal levels in all head channels before equalization.) The required wide range of phase shift is accomplished by two stabilized multivibrators in series, V10 and V14. The 240-cps tone-wheel square wave from stage V9A (Figure CS-3) is differentiated by a 220-mmf capacitor and 47K resistor to form positive and negative "pips" at the edges of the square wave. Diodes CR6 and CR5 permit only the negative pips to pass through to trigger multivibrator V10. V14 is an identical multivibrator triggered by the trailing edge of the pulse produced in V10 by means of the differentiator and diode coupling network attached to the stabilizing diode in the cathode circuit of the right side of V10. In both multivibrators, the left side conducts when the circuit is in the "resting" condition, but is driven below cut-off when a negative trigger is applied to the plate of the right side. The length of time the left side remains cut off (and hence the pulse period) is determined both by the time constant in the grid circuit (in this case, the 820-mmf capacitor and 1.5-megohm resistor) and by the voltage range available to alter the charge on the coupling capacitor. The time constants of both V10 and V14 are relatively fixed, but a control is provided to adjust the absolute

voltage on the grids of both stages. This control is marked CONTROL TRACK PHASE, and is located on the main control panel.

The output pulse at the cathode of V14 is differentiated by the 220-mmf capacitor and 100K resistor in the grid circuit of V9B. The positive "pip" is suppressed by grid clipping; when V9B is driven positive, it draws grid current and attenuates the signal by the action of the 1000-ohm grid resistor in series with the relatively low grid-to-cathode impedance. The positive pulse in the plate circuit of V9B is further clipped by diode CR3 to form a clean discharge pulse for the sawtooth generator, V8. The sawtooth generator is of the so-called "bootstrap" type. During the intervals between pulses, the 6800-mmf capacitor tends to charge up toward +280 volts at a rate determined by the 2.7-megohm and 390-kilohm resistors. From a cathode follower, V8B, the rising voltage is coupled back to the positive end of the 2.7-megohm resistor through a large (0.47 mf) coupling capacitor. This rising voltage applied to the top of the current-limiting resistor tends to make the voltage drop across it uniform throughout the sawtooth period, resulting in a highly linear sawtooth waveform across the 6800-mmf capacitor. When a positive pulse is applied to the grid of V8A, the storage capacitor is rapidly discharged through the tube, and a new sawtooth cycle begins. The output from V8B is coupled to a potentiometer, which serves as the gain control for the servo loop.

ERROR DETECTOR

The error detector circuit in which the control-track and tone-wheel signals are compared is shown in Figure CS-6. The 240-cps sine wave from the control track playback amplifier is amplified in V12B, then further amplified and clipped in V13. The latter stage is a cathode-coupled circuit which provides amplification without a phase inversion. The signal at the plate of the right side of V13 is essentially a square wave, which is differentiated by C13 and R27. The positive "pip" resulting from this differentiation is suppressed by grid limiting in V12A, but the negative "pip" drives V12A toward cutoff and produces a sharp positive pulse in the plate circuit. The next stage, V7B, is normally biased below cutoff, but the peaks of the positive pulses from V12A turn it on to provide keying pulses for the clamp-type phase detector through transformer T2. The phase detector uses two double diodes (V5 and V6) in a bridge-type circuit. The diodes are non-conducting except for brief intervals at the tips of the sampling pulses delivered by T2 – the 1.0-mf capacitor in series with the secondary of T2 maintains its charge between pulses (except for the relatively slow discharge through the 1-megohm resistor) to keep the diodes in a non-conductive state between sampling instants. When the diodes are closed, capacitor C18 is connected through the relatively low diode impedance to the LOOP GAIN potentiometer where the tone-wheel sawtooth signal is present. During these sampling instants, capacitor C18 tends to

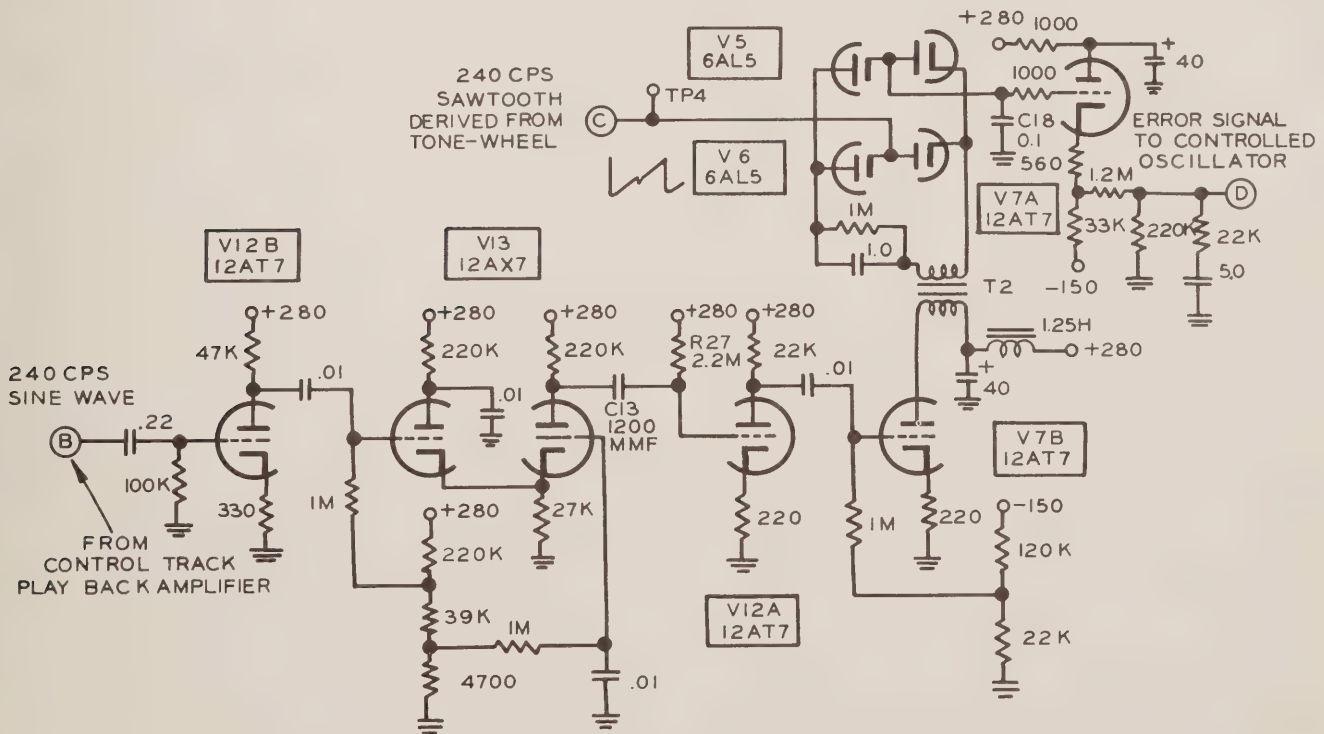

Figure CS-6. Error Detector Circuit for Capstan Servo

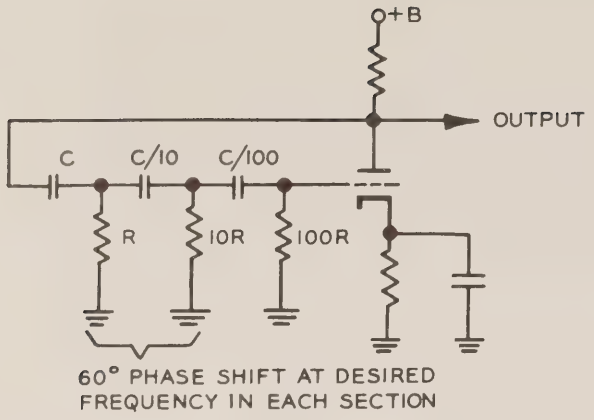

Figure CS-7. Generalized Schematic Diagram of a Common Version of the Phase-Shift Oscillator

charge up to whatever voltage is provided by the sawtooth. The proper sampling point is at the center of the long slope on the sawtooth. If the sampling pulses tend to occur too fast, implying that the tape is being pulled too fast, the sampling pulses will move downward along the slope, thereby reducing the voltage across C18. Likewise, if the sampling pulses become too slow relative to the sawtooth, the voltage across C18 will increase because the sampling will occur at a higher point on the sawtooth. The sampling point can be observed by connecting an oscilloscope at test point TP4, because a slight transient is visible on the sawtooth waveform. The voltage across C18 is applied to a cathode follower, V7A, whose output circuit includes an attenuator to provide a proper level for the 60-cps controlled oscillator. The 22K resistor and 5.0-mf capacitor reduce the gain of the system for all except very low frequencies, and modify the phase-shift characteristic to minimize the risk of oscillation or hunting.

CONTROLLED OSCILLATOR

The controlled oscillator used in the capstan servo system is of the so-called phase shift type. A generalized schematic diagram for a common version of this type of oscillator is shown in Figure CS-7. In any oscillator, of course, there must be some form of positive feedback, some form of frequency selectivity, and enough gain to overcome the losses in the circuit (that is, the gain around the feedback loop must be greater than unity at the frequency of oscillation). In the phase shift oscillator, feedback from plate to grid of a single stage is provided through a multi-section network which introduces a 180-degree phase shift at the desired frequency of oscillation. (Direct feedback from plate to grid would be negative, but the 180-degree phase shift makes the feedback positive.) It is common practice to design the phase shift network in three stages, each contributing approximately 60 degrees. In the common approach illustrated in Figure CS-7, the same time constant (RC product) is used in each section, but the component values in successive sections are scaled upward or downward by a factor of 10 in order to reduce the loading effects on the previous section. Each section introduces a voltage loss, which must be overcome by the gain of the tube. This type of oscillator is attractive for many low-frequency applications, because it requires no large inductors. In the case of the capstan servo, the phase-shift type of oscillator was chosen primarily because it is readily adaptable to both manual and automatic frequency control.

The actual circuit used in the capstan servo is shown in Figure CS-8. The phase-shift oscillator is V4A, and the circuit surrounding it has been drawn with the closest possible similarity to the generalized diagram in Figure CS-7. The first part of the 3-section phase-shift network includes a pair of adjustable resistors which provide manual adjustment of the oscillator's frequency through their effect on the phase shift of the first section. A relatively wide-range control is provided for manual operation; this permits the speed of the tape to be varied enough to bring two machines into audio synchronism when they are playing back identical programs. For automatic (or servo-controlled) operation, a limited-range manual control is provided to set the free-running frequency of the oscillator at the proper value which will permit the error detector to work in the middle of the sawtooth slope. The wide-range manual control is located on the machine's main control panel, and the relay which switches between manual and automatic operation is actuated by pushing in on the manual speed control knob. (The same relay also shorts out the error signal to completely disable the automatic control when manual operation is desired.)

The resistance in the second section of the phase-shift network consists of a 121K resistor in series with the output of cathode follower V3. A sample of the signal at the top of the 121K resistor is applied to the grid of V1 through a voltage divider consisting of a 3.3-megohm and a 47K resistor. This signal is amplified by V1 and applied to cathode follower V3 with a phase inversion. Capacitor C47 serves primarily to compensate for the phase shift introduced by the inter-stage coupling network between V1 and V3. Capacitor C46 is a d-c block between the cathode of V3 and the grid of V1. Because the signal applied by the cathode follower in series with the bottom end of the 121K resistor is out-of-phase relative to the signal at its top end, the apparent resistance in this section of the phase-shifting network is somewhat less than the actual value. The amount of this apparent reduction is determined by the gain of the combination of V1 and V3. Since the grid of V1 is returned to the source of the error signal developed by comparison of the control track and tone wheel signals, the resistance in the second section of the phase shifter is effectively "modulated" by the error

signal. If the error voltage tends to rise, implying that the capstan motor is running too slow, the gain of V1 will increase slightly, causing a decrease in the apparent resistance of the phase-shift network. This decreased resistance causes an increase in the frequency at which the phase shift totals 180 degrees, and thus slightly increases the frequency of the oscillator. Since the motor is driven synchronously, it also increases slightly in speed to restore the proper speed to the tape.

The third section of the phase-shift network is a simple capacitor and resistor. The output of the oscillator is attenuated by a 1.5-megohm resistor in series with a 100K resistor, and applied to the grid of a cathode follower, V4B. In the output of this cathode follower, there are two phase-shift networks to provide two signals in phase quadrature, and a pair of potentiometers for balancing the two phases. Note that the OFF-ON relay stops the capstan motor by grounding the signal at the grid of V4B. In the record mode, relays are used to short out the control signal at the grid of V1 and to substitute a 60-cps signal derived from the power line at the grid of V4B.

OUTPUT AMPLIFIERS

The output amplifiers for the capstan servo are identical to those described in connection with the head-wheel servo system (see Figure HW-9) except for the connections in the secondary side of the output transformers. Since the capstan motor is a two-phase type, it is unnecessary to use the Scott transformer connection to convert from 2-phase to 3-phase power.

SET-UP AND OPERATING ADJUSTMENTS

In comparison with the head-wheel servo, the capstan servo has relatively few adjustments, and is quite easy to set up. The only controls in the output amplifiers (Figure HW-9) are the bias adjustments, which should be set with no signal present to give a current of 28 milliamperes in each output tube. To assure a proper power level to the capstan motor, the PHASE 1 AMPLITUDE and PHASE 2 AMPLITUDE controls (Figure CS-8) should be adjusted while the machine is in the playback mode to give 115 volts rms at the power amplifier outputs (for convenience, test points TP5 and TP6 – not shown on the simplified schematics – are provided on the cap-

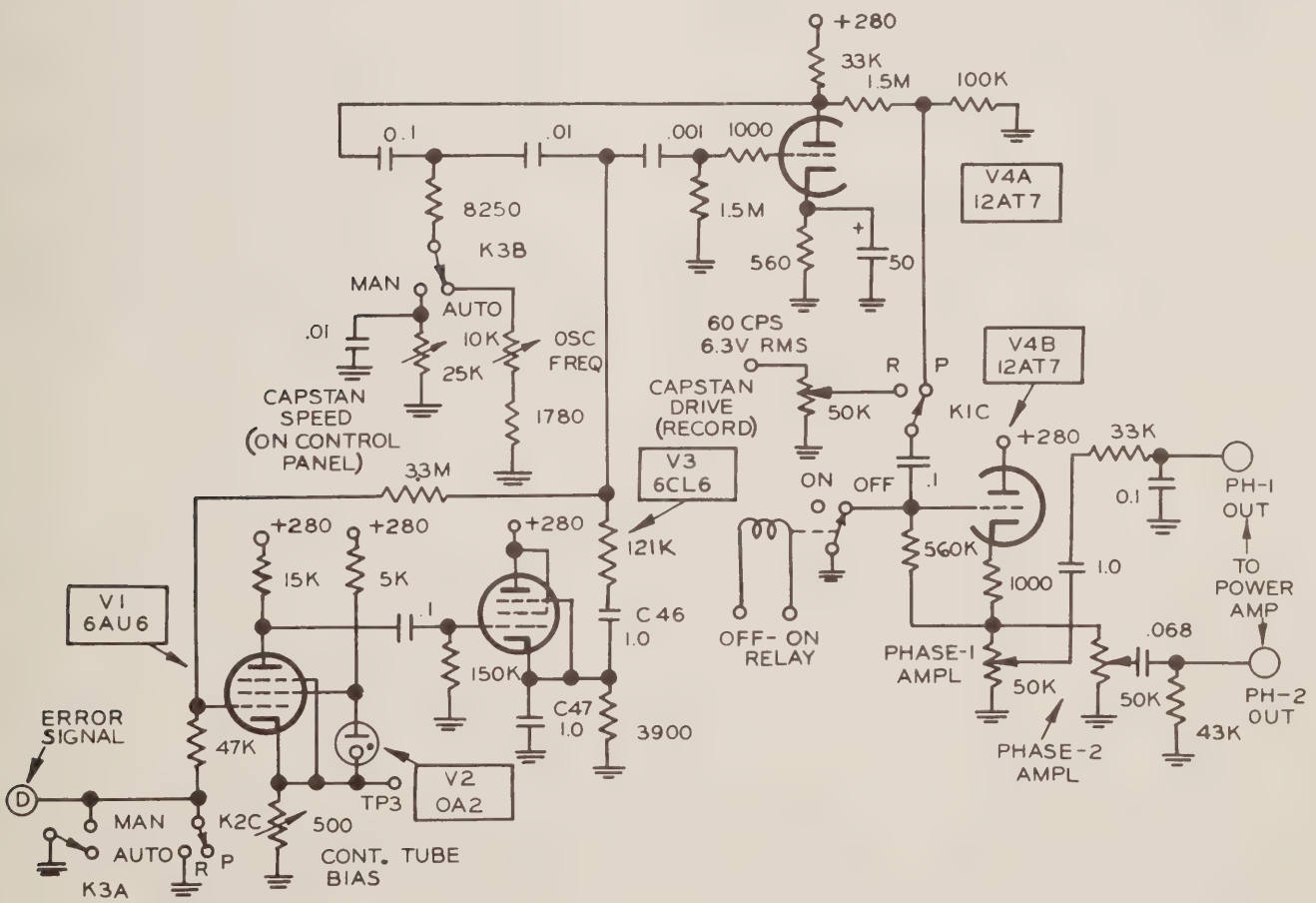

Figure CS-8. Controlled Oscillator for Capstan Servo

stan servo chassis to check these voltages). The CAPSTAN DRIVE RECORD control (Figure CS-8) should be adjusted to give the same power amplifier output readings when the machine is operated in the set-up or record modes.

Proper recording levels for the control track are set with the aid of the built-in waveform monitor and control track record current meter. With the machine operating in the record mode, the 240 RECORD AMPLITUDE control (Figure CS-3) should be adjusted to give a reading of 0.5 on the meter (located on the main control panel). The FIELD PULSE AMPLITUDE control should be adjusted to make the field pulse on every fourth cycle equal to the 240-cps sine wave in peak amplitude as viewed with the waveform monitor switched to the C.T. RECORD position. The field pulse should be positioned as shown in the waveform sketch to the left of the monitor output jack in Figure CS-3; the control which sets this position is located on the tone-wheel amplifier chassis, and is marked 240 SQUARE WAVE DELAY.

The CONTROL TUBE BIAS control (Figure CS-8) should be set to give +4.5 volts d-c at the cathode of V1 (TP3) while the machine is running in the playback mode, but with no tape in place. The OSCILLATOR FREQUENCY control should be set while playing back a normally-recorded tape and looking with an oscilloscope at the sawtooth input to the phase detector (TP4, Figure CS-6). The sampling "pip" that is visible on the sawtooth waveform should be centered on the long slope of the sawtooth. The LOOP GAIN control (Figure CS-5) should be advanced until the position of the pip begins to waver (indicating instability), and then backed off slightly for operation at maximum permissible gain.

The CAPSTAN SPEED and CONTROL TRACK PHASE controls located on the main control panel are actually outside of the capstan servo loop. The CAPSTAN SPEED control is operative only when the knob is pushed in to close the switch contacts which operate relay K3 (shown in Figure CS-8) to disable the automatic servo system in favor of manual control. This control is normally used only when synchronizing two machines playing back the same program. The picture signal is normally unusable when the servo loop is disabled, but the audio signal is still intelligible, and it is possible to speed up or slow down one machine until the two audio signals match in time, at which point the CAPSTAN SPEED CONTROL knob should be released to permit the servo system to resume control. The CONTROL TRACK PHASE control determines the effective phase of the tape relative to the rotating video head wheel. For proper operation, each video head should be centered over one of the transverse tracks on the tape. If the phase is off only slightly so that the head is only partially on the track and partially on an adjacent guard band, the signal-to-noise performance deteriorates because of the loss in signal strength. If the phase is more seriously misadjusted so that each head actually passes over portions of two adjacent tracks, the picture breaks up into a useless herringbone pattern. The control track phase is best set while looking with the waveform monitor at the output of the 2 x 1 switcher (just ahead of the FM demodulator). Proper tracking is indicated by maximum level in this waveform. If the levels from the four heads appear quite different, it is often possible to equalize them to some degree by adjusting the CONTROL TRACK PHASE control far enough to move the heads to entirely different tracks. If, for example, a recording was made with a slightly sub-standard head in one channel, it can be played back with the highest-gain head passing over the slightly sub-standard tracks, so as to equalize the signal-to-noise ratio as far as possible.

SHOE SERVO SYSTEM

OBJECTIVES

The purpose of the shoe servo system is to control the position of the vacuum shoe which guides the tape into contact with the rotating video head-wheel. To provide the intimate head-to-tape contact required for recording at very high frequencies, the position of the tape guiding shoe is so adjusted that the rotating heads indent the tape to about the degree indicated by the scale drawing in Figure SS-1. It is difficult to show in a two-dimensional sketch the actual nature of the local distortion in the tape as it passes over the heads. Because the pole pieces of the video heads protrude above the rim of the head-wheel by about one to four mils (depending upon head wear), the tape is actually stretched in a localized "dimple" which travels across the tape as the head rotates. The depth (or height) of this "dimple" depends upon the precise location of the shoe relative to the rotating wheel.

In addition to providing good head-to-tape contact, the slight stretching of the tape resulting from the indentation of the video heads is necessary to compensate for minor dimensional variations resulting from wear, slight differences between machines, and expansion or contraction in the tape itself. During recording operations, the shoe is maintained in a fixed position, resulting in a fixed degree of stretch in the tape; the stretch must be great enough to permit playback in a state of tension under the least favorable conditions likely to be encountered. (Unfortunately, it is not practical to *compress* the tape during playback, but it is relatively easy to stretch it.) During playback, the tape should be stretched only enough to match the conditions under which it was recorded, and the shoe servo system is provided to make the required adjustments automatically.

If the shoe position is not correct, resulting in either too much or too little stretch of the tape, the relative head-to-tape speed is not quite correct and there are slight timing errors in the output signal, just as in the case of an audio tape recorder running at an improper speed. The *average* timing remains correct, however, because the angular velocity of the head-wheel is maintained at a proper value by the head-wheel servo system. The timing errors appear in the form of discontinuities at the instant of switching

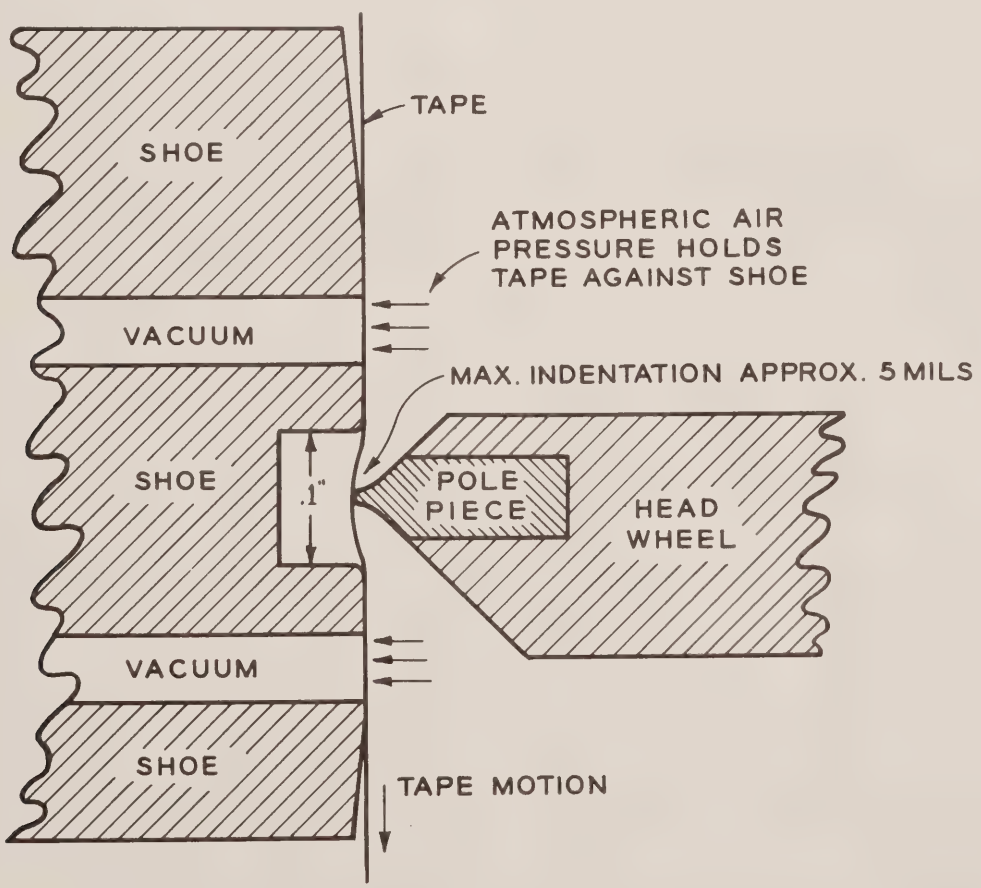

Figure SS-1. Cross-Section Drawing of the Tape Guiding Shoe and Video Head-Wheel, Illustrating the Indentation of the Tape by the Video Heads

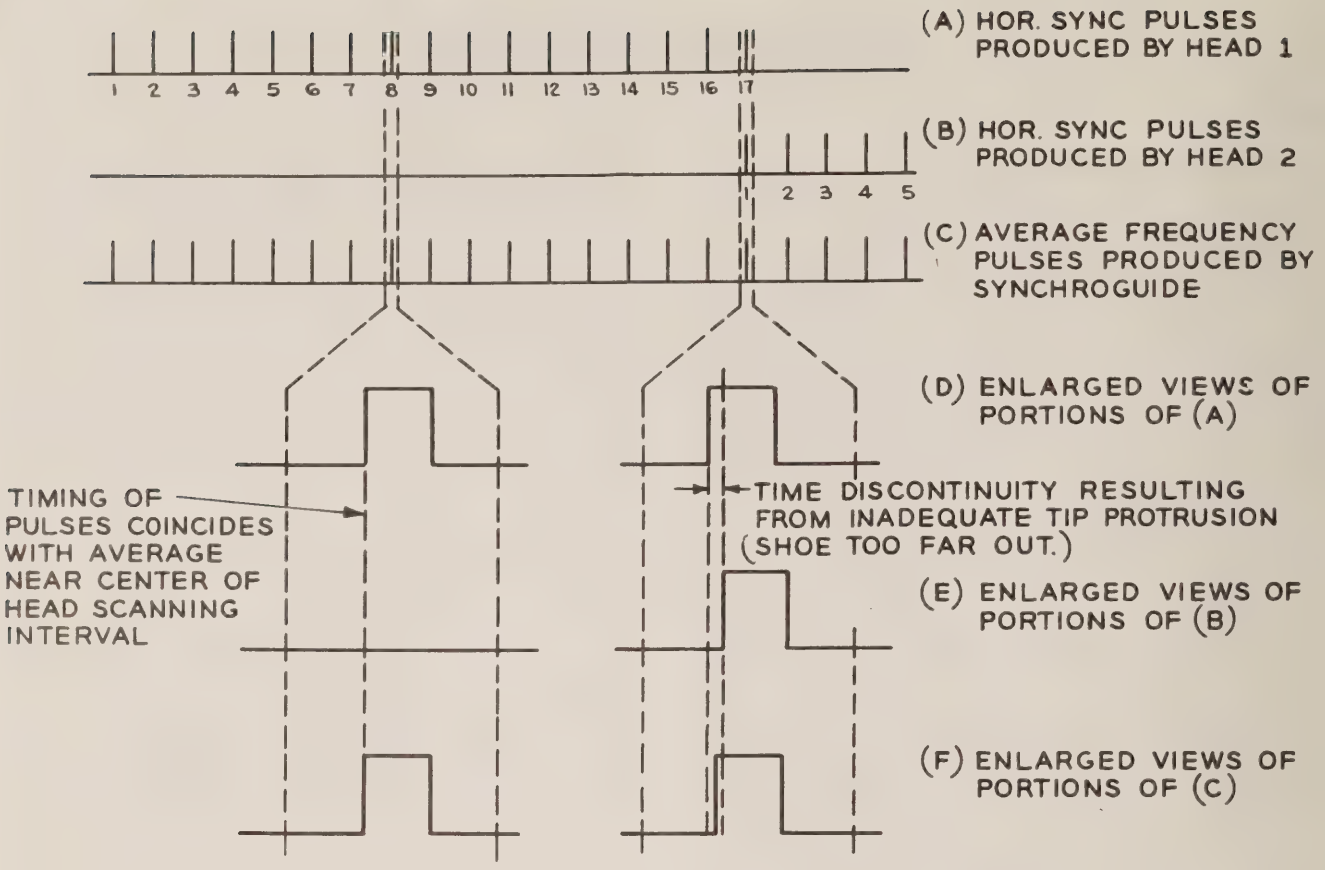
(A) HOR. SYNC PULSES PRODUCED BY HEAD 1
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
(B) HOR. SYNC PULSES PRODUCED BY HEAD 2
1 2 3 4 5
(C) AVERAGE FREQUENCY PULSES PRODUCED BY SYNCHROGUIDE
(D) ENLARGED VIEWS OF PORTIONS OF (A)
TIMING OF PULSES COINCIDES WITH AVERAGE NEAR CENTER OF HEAD SCANNING INTERVAL
TIME DISCONTINUITY RESULTING FROM INADEQUATE TIP PROTRUSION (SHOE TOO FAR OUT.)
(E) ENLARGED VIEWS OF PORTIONS OF (B)
(F) ENLARGED VIEWS OF PORTIONS OF (C)

Figure SS-2. Waveform Sketches Illustrating Timing Errors Resulting from Shoe Position Errors

from head to head, as indicated in Figure SS-2. While only horizontal sync pulses are shown the same timing errors also occur for all picture signal components.

If a train of pulses containing slight timing discontinuities is applied to a horizontal oscillator of the synchroguide type with a "flywheel" time constant somewhat greater than the 16-line head-scanning interval, it is possible to develop a steady train of average-frequency pulses in which the timing variations are eliminated, as shown at (c) and (f) in Figure SS-2. Since most horizontal-deflection circuits in television receivers behave in this general fashion, the appearance of shoe position errors in television pictures is about as indicated in Figure SS-3. The "flywheel" effect in the deflection oscillator causes the line scanning to occur at essentially constant frequency, but the timing errors in blanking and all other signal components causes an effect that various people have called "jogging", "skew", or the "venetian blind effect". The jogs occur in bands of 16 lines per field, or 32 lines in properly interlaced frames, since approximately 16 lines are recorded during each head-scanning interval. The figure illustrates the case of inadequate head-to-tape pressure resulting from the shoe being too far out. If the shoe is in too far (excessive pressure), the result is very similar, but the "jogs" slope in the opposite direction. As a rough "rule of thumb", an error of about 1 mil in shoe position results in jogs that are off-set by about 1.25% of the picture width. Shoe position is correct at the point where the jogs completely disappear.

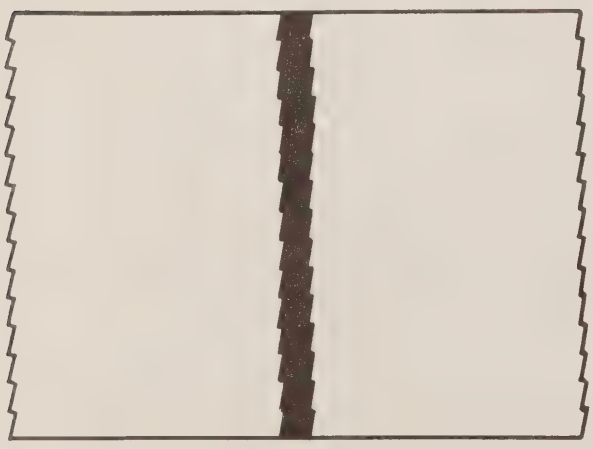

Figure SS-3. Sketch of a Television Raster Showing Effect Produced by Inadequate Head-to-Tape Pressure Resulting from an Error of About 1 mil to Shoe Position

OVERALL BLOCK DIAGRAM

A simplified block diagram of the shoe servo system is presented in Figure SS-4. The main output

device for the system is a motor that normally remains stationary, and moves only slightly in one direction or the other in response to error signals. In general, the motor automatically seeks to position itself so as to keep the error signal at zero.

The main error detector for the shoe servo system is not mounted on the shoe servo chassis, but is located on the 2 x 1 switcher (where it also performs additional functions related to the head-switching and sync-restoration operations). The error detector is a simple adaptation of a conventional synchroguide circuit; a circuit tuned to 960 cps is inserted in the plate circuit of the synchroguide's control tube to sense the presence of timing variations at the head-switching rate. The polarity of the 960 cps signal developed in this circuit indicates the direction of the timing errors. In the circuitry on the shoe servo chassis, the 960 cps signal is amplified, clipped, and rectified. To preserve the direction sense in the error signal, the rectifier is a bi-directional type, utilizing 960 cps clamping pulses derived from the tone-wheel attached to the head-wheel motor. The clipping is sufficiently severe that if there is any significant error signal at all, the rectifier produces a fixed d-c level of a polarity indicating the direction of the error. The rectified error signal is converted to 60 cps a-c by the action of a chopper-type modulator, and then amplified to the power level necessary to drive the shoe positioning motor. The motor is a two-phase type in which one phase is continuously excited by the power line, while the other is driven by the amplifier. The motor develops torque only when a signal is delivered by the amplifier, and the direction of this torque depends upon the polarity of the amplifier signal. The motor then drives the shoe through an appropriate mechanical coupling. The motor movement is limited to only a few revolutions, and the maximum displacement required for the shoe is only about 5 mils. The servo loop is completed through the video heads, slip rings, video playback system, and a sync separator (the sync separator is also mounted on the 2 x 1 switcher chassis).

A much smaller servo loop is used for manual positioning of the shoe during recording operations (and during special cases of playback operation, to be discussed later). The switches shown in Figure SS-4 are actually relay contacts, controlled by switches on the main control panel and interlocked with the main RECORD and PLAY buttons. For manual operation, a potentiometer on the motor shaft is compared with the setting of a second potentiometer which is mounted on the control panel. The motor turns until the voltage at the arm of the motor potentiometer is the same as that on the manual "shoe position"

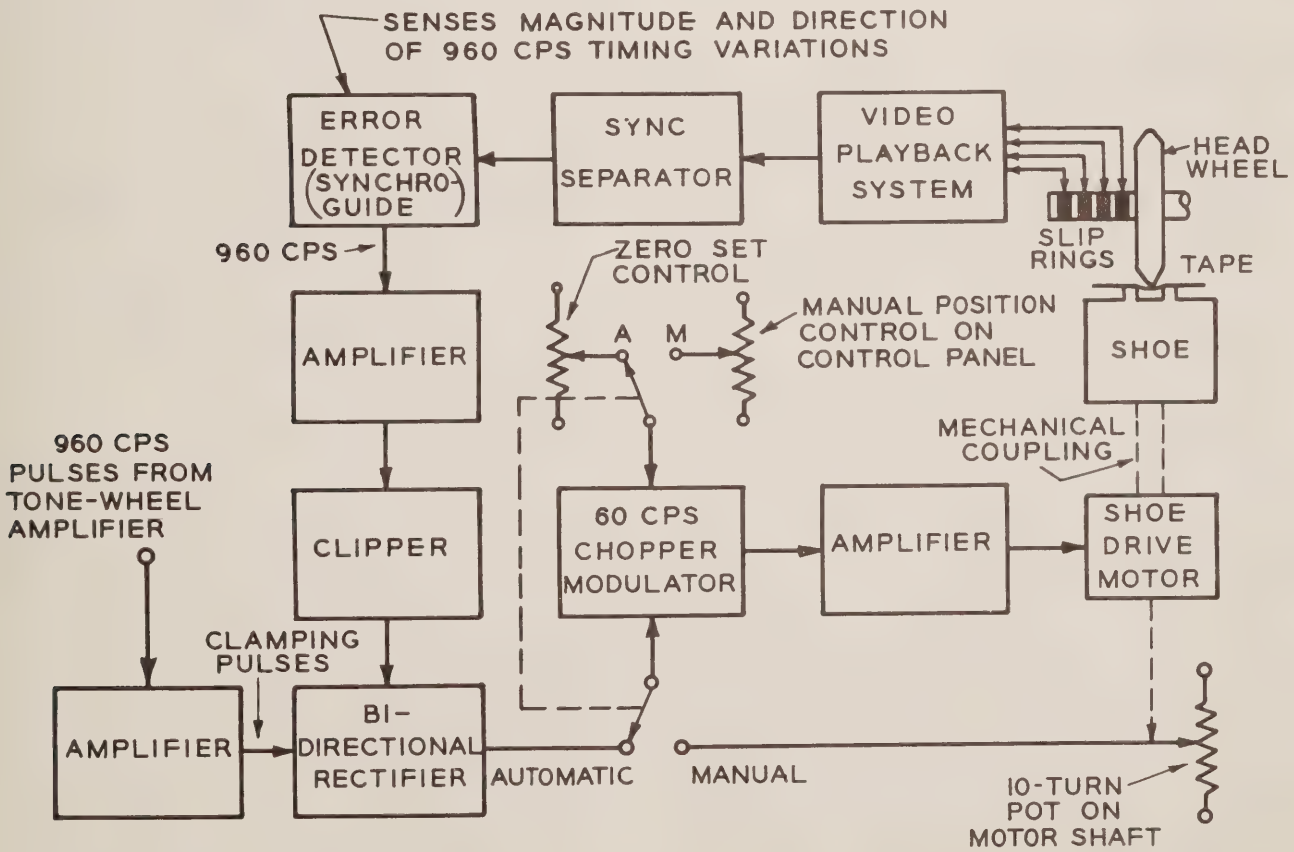

Figure SS-4. Simplified Block Diagram of Shoe Servo System

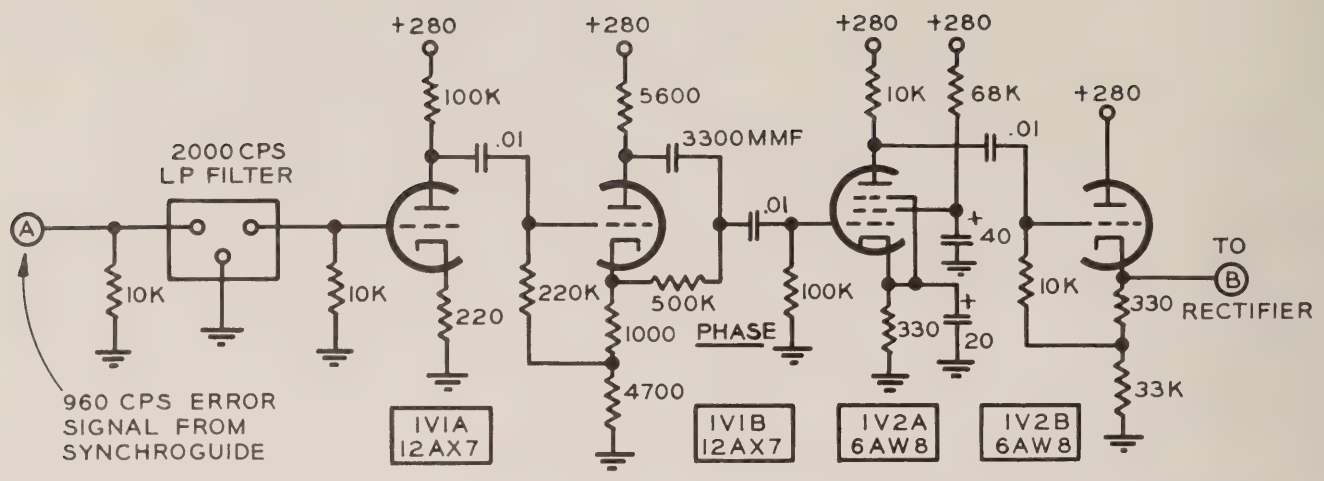

Figure SS-5. Amplifier and Phase Shifter for 960-Cps Error Signal

control, resulting in zero signal at the output of the chopper. Through the use of this relatively simple positioning-type servo, the manual SHOE POSITION control is, in effect, directly coupled to the motor shaft.

The circuit details related to the sync separator and synchroguide error detector are discussed in the article describing the 2 x 1 switcher, but the circuits actually mounted on the shoe servo chassis will be described here with the aid of simplified schematic diagrams.

960 CPS ERROR SIGNAL AMPLIFIER

The amplifying circuits for the 960 cps error signal developed in the synchroguide are shown in Figure SS-5. A "packaged" 2000 cps low-pass filter is used to eliminate the line-frequency components which are also present in the synchroguide output. 1V1A is a conventional voltage amplifier, stabilized by cathode degeneration. The adjustable phase shifter in the output side of 1V1B makes it possible to adjust the peaks (or the valleys) of the 960 cps error signal to coincide with the 960 cps tone-wheel pulses used for clamping purposes in the bi-directional rectifier to be discussed presently. Further amplification occurs in 1V2A, and cathode follower 1V2B provides a relatively low output impedance for the clipping circuits which precede the rectifier.

ERROR SIGNAL RECTIFIER

Figure SS-6 shows the bi-directional error signal rectifier and the clamping and clipping circuits closely related to it. The 960 cps signal from the cathode follower 1V2B is limited to a maximum peak-to-peak swing of about 1 volt by the clipping action of diodes 1CR1 and 1CR2. (When either diode conducts, the signal is sharply attenuated by the 100K resistor in series with the low forward impedance of the diode.) The clipped signal is then clamped by 1V3 and 1V4, which are keyed by tone-wheel pulses introduced through 1V5A (a voltage amplifier) and 1V5B (a phase splitter). Diodes 1V3 and 1V4 are connected in a bridge circuit, and remain open except during the tone-wheel pulse intervals. When the diodes conduct, the right side of the .47 mf capacitor is tied through a low impedance to ground. Whether the clamping pulses occur during the positive or negative half-cycles of the error signal depends upon the polarity of the 960 cps signal from the synchroguide, which in turn depends upon the direction of the timing errors. The "smoothed" d-c voltage at the output of the integrating network consisting of the 100K resistor and 0.22 mf capacitor is therefore either plus or minus, depending upon the direction in which the shoe must be moved to eliminate the error. When the shoe position is correct, both the 960 cps error signal and the rectified signal go to zero.

MODULATOR AND MOTOR DRIVE CIRCUITS

Most of the circuits shown in Figure SS-7 are mounted on a subchassis which is purchased as a complete subassembly from the Brown Instruments Division of the Minneapolis-Honeywell Regulator Company. The circuits represent an adaptation of a standard servo system designed for a variety of positioning-type applications.

To avoid the stability problems frequently associated with high-gain d-c amplifiers, the rectified error signal is converted to a 60 cps a-c signal by 2G1, a chopper modulator driven from the power line (through a 6.3 volt winding on the power transformer). In the "automatic" operating condition, the chopper develops an output signal only if there is a difference between the error signal and the setting of a control marked ZERO SET – the latter control is used only to cancel out any small voltage off-set in the error signal that may result from hum pickup or slight unbalance in the clamp-type rectifier. In the "manual" operating condition (used in the record mode), the chopper develops an output signal whenever the setting of the manual SHOE POSITION control does not coincide with the setting of a

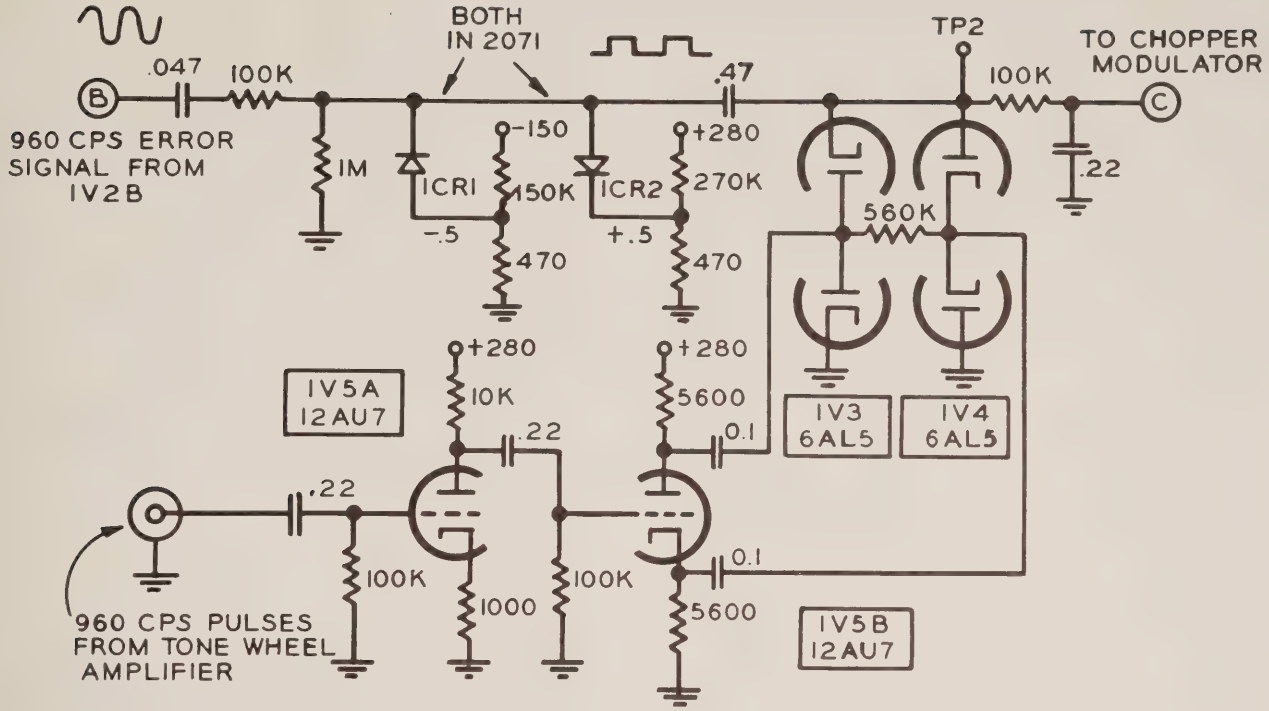

Figure SS-6. Bi-Directional Rectifier for Shoe Servo Error Signal

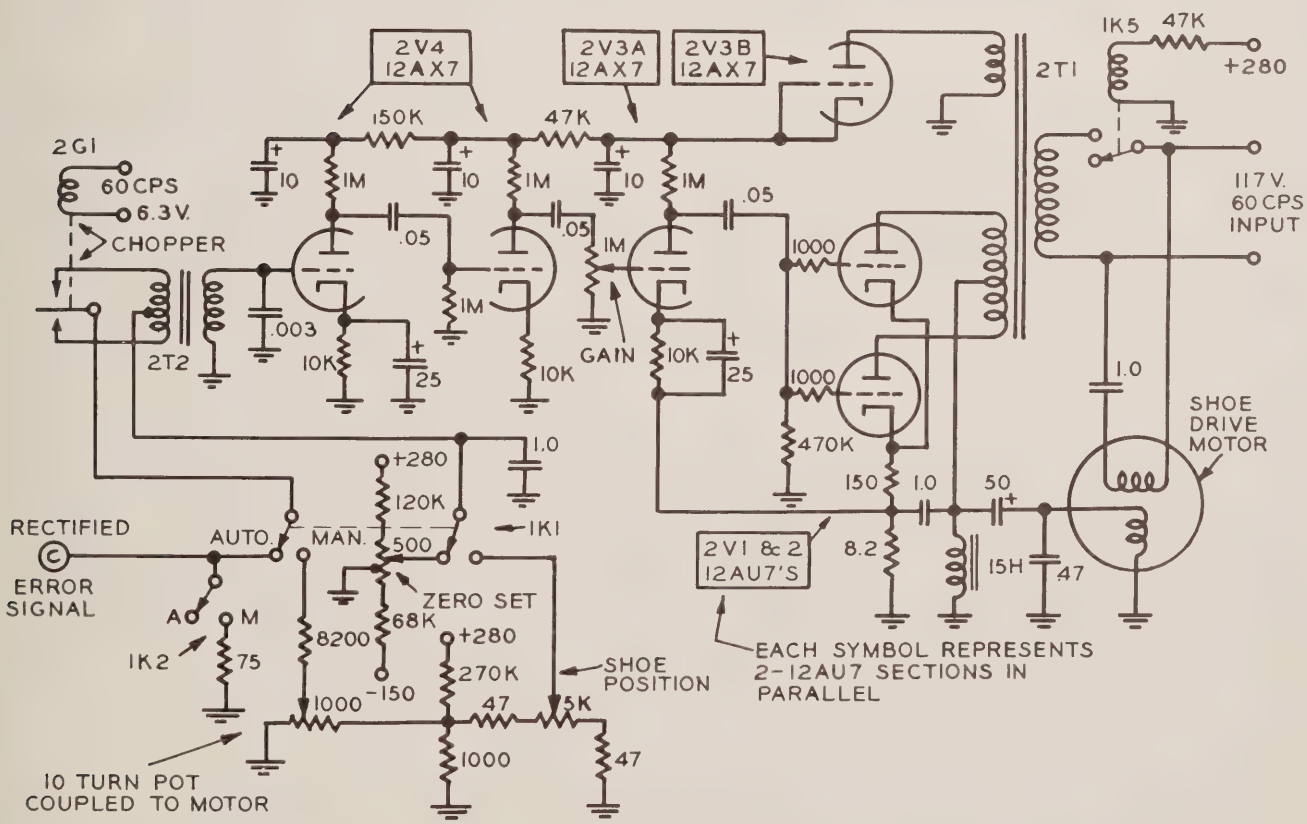

Figure SS-7. Modulator and Motor Drive Circuits for Shoe Servo

potentiometer directly coupled to the motor shaft. A .003 capacitor at the output of transformer 2T2 suppresses most of the harmonics of the 60 cps signal generated by the chopper.

Three stages of voltage amplification are provided by 2V4 and 2V3A. 2V3B functions as a rectifier to provide the +B power for the voltage amplifier; note that thorough decoupling is provided between the voltage amplifier stages. The built-in power supply for the circuits in the Brown Instruments subassembly is interlocked with the +B power supply for the rest of the circuits on the shoe servo chassis by means of relay 1K5, shown in the upper right-hand corner.

The shoe drive motor is a two-phase type in which one phase is driven directly from the power line through a 1.0 mf phase-shifting capacitor. The other phase is driven by the 60 cps ripple voltage at the output of a pair of controlled rectifiers, 2V1 and 2V2. If there is no error signal on the grids of these tubes, there is no 60 cps component in the output. The d-c component is prevented from flowing through the motor winding by a 50-mf blocking capacitor; the 15H choke provides a d-c current path. If an error signal is present, however, the 60-cps grid signal is in phase with the plate voltage pulse on one side of the circuit and out of phase with the plate voltage pulse on the other side. (Proper phase relationships between plate and grid circuits are assured by the fact that the phase lag introduced by the chopper is compensated by the phase lead introduced by the interstage coupling networks in the voltage amplifier.) The net result is that one-half-cycle is amplified more than the other in the controlled rectifier, and a 60-cps component appears at the output. Filtering to emphasize this 60-cps component and to suppress the higher harmonics is provided both by the 1.0-mf filter capacitor between the center tap of the transformer and the common cathode circuit, and also by the 0.47-mf capacitor which resonates the parallel combination of the motor winding and the 15H choke at 60-cps. Torque is produced by the motor only when a 60-cps signal is delivered by the controlled rectifier, and the direction of this torque depends upon the phase (or polarity) of the 60-cps signal. A small amount of positive current feedback is coupled from the common cathode circuit of 2V1 and 2V2 to the cathode of 2V3A to provide velocity damping for the motor.

CONTROL CIRCUITS

Figure SS-8 shows both manual and automatic control circuits for the shoe servo system. The MANUAL/AUTOMATIC switch on the main control panel (shown at upper right) controls the input to the chopper modulator through relay 1K1. Automatic operation is possible only in the playback mode, since the source of +24 volts to operate 1K1 is interlocked with the PLAY pushbutton, but the switch

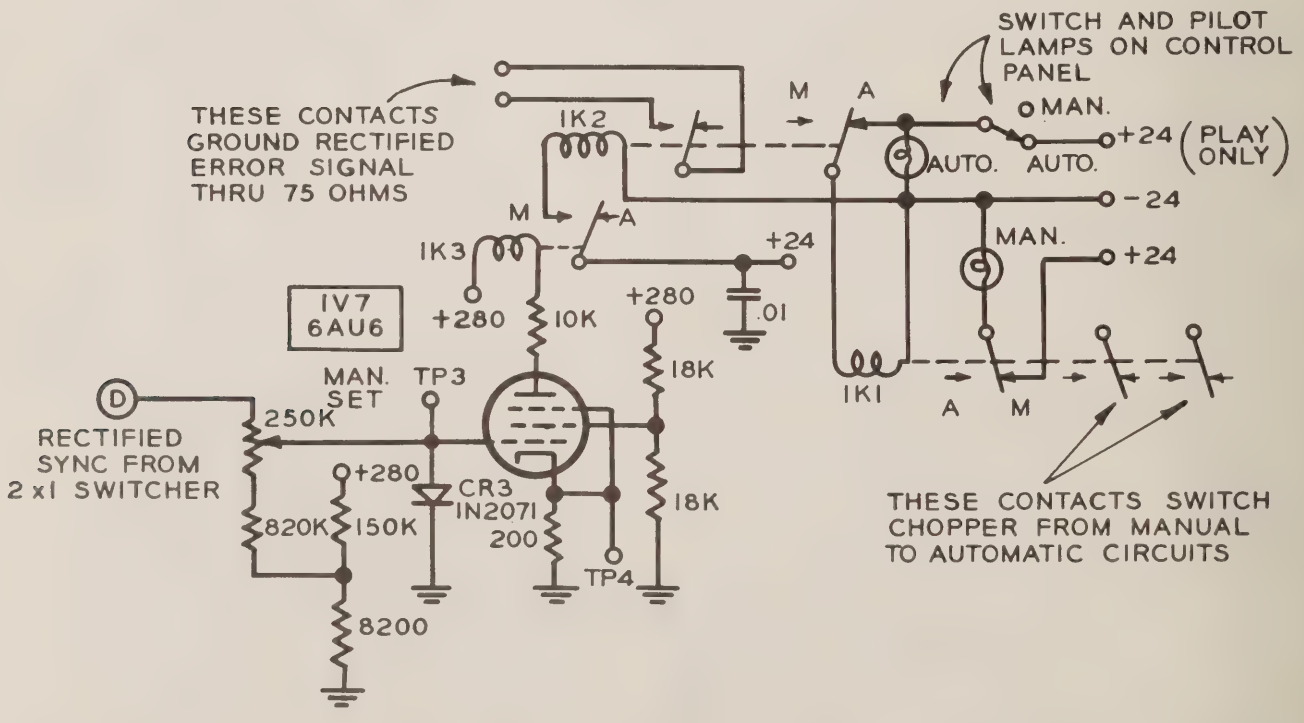

Figure SS-8. Control Circuits for Shoe Servo

may be left in the AUTOMATIC position so that the machine is always ready for proper playback upon pushing the PLAY button. 1V7 is a special control tube to disable the shoe servo system when the signal at the output of the video playback system drops below a pre-determined level and becomes sufficiently noisy that the operation of the shoe servo system is less reliable than manual operation. 1V7 is normally held in a cut-off condition by rectified sync pulses derived from the sync separator on the 2 x 1 switcher chassis. The sync pulses before rectification are negative-going, and provide enough negative voltage to override the positive bias applied through the MANUAL SET potentiometer. If the signal level drops ahead of the sync separator, the negative voltage developed by rectifying the sync pulses also drops and permits 1V7 to come "on", thus closing relay 1K3, which in turn closes 1K2 and opens 1K1. Diode CR3 limits the voltage on the grid of 1V7 to nominally ground potential. Note that both pilot lights are on when the MANUAL/AUTOMATIC switch is on AUTOMATIC but the action of 1V7 has automatically thrown the circuit over to the manual condition. The illumination of both pilot lights thus serves as a visual indication that the sync level has dropped below the pre-determined threshold, and that manual setting of the shoe position is desirable.

SET-UP AND OPERATING ADJUSTMENTS

In addition to the actual operating controls on the main control panel, whose functions are quite obvious, there are only four set-up adjustments in the shoe servo system: PHASE, MANUAL SET, ZERO SET, and GAIN. To set the phase adjustment, the machine should be set-up to playback a normally recorded test tape with the MANUAL/AUTOMATIC switch in the MANUAL position and the SHOE POSITION control set at about one mil from zero "jog". The switch is then thrown to the AUTOMATIC position. The PHASE adjustment is then turned to the maximum position in the direction that results in correction of the "jog". While still playing back the test tape, the MANUAL SET control should be adjusted for a voltage of −6.5 volts at the grid of 1V7 (TP3, Figure SS-8). The ZERO SET adjustment (Figure SS-7) should be set with the machine playing back a test tape in the AUTOMATIC condition. When this control is properly set, the servo system will stabilize the shoe position at the position giving no "jogs" in the picture or zero 960-cps signal at test point TP-2 (Figure SS-6). The GAIN control should be advanced as far as possible without introducing instability along vertical edges of the picture, indicating a tendency toward "hunting" or oscillation. To check the operation of the shoe servo system after making these adjustments, it is desirable to run through a piece of tape in which the shoe position was deliberately changed several times during recording; the shoe servo should respond to these changes by automatically restoring the shoe to the position which results in jog-free operation.

For manual operation in the RECORD mode, the SHOE POSITION control should be calibrated with the aid of the mechanical shoe position adjustment (on the head-wheel panel assembly) so that a zero setting of the control corresponds to the minimum head-to-tape pressure which yields a normal signal-to-noise ratio in the picture. This adjustment is accomplished by playing back a test tape (or any normally-recorded tape) in the MANUAL condition with the SHOE POSITION control set at zero, and setting the manual adjustment for minimum pressure while watching the picture – the "jogging" effect should be ignored while making this adjustment, since only the signal-to-noise ratio is significant. Once properly calibrated, the full range of the SHOE POSITION control then corresponds to about 5 mils of additional movement to increase the head-to-tape pressure and the tape stretch. The setting of the SHOE POSITION control for recording operations depends upon the degree of wear in the head-wheel, and the objective of the recording operation to be performed. If the objective is simply time-delay – that is, if the recording is to be played back on the same machine almost immediately, and is not to be saved for later use – it is desirable to use a bare minimum of head-to-tape pressure so as to minimize wear on the head and the tape. If, on the other hand, the recording is to be played back on another machine or at a much later time, it is important that it be recorded under sufficiently "standard" conditions that proper playback can be assured under any reasonable conditions of tape shrinkage or head wear in the playback machine. If the head-wheel used for recording is nearly new and has maximum tip protrusion above the rim of the head-wheel, it is necessary to move the shoe position in by an amount equal to the tip protrusion minus 0.0005″ from the "zero" position to assure that the tape can still be played back under a condition of stretch on a machine with a head-wheel that is nearly worn out. If the head-wheel used for recording is also approaching the wear-out point, it is not necessary to use as much head-to-tape pressure.

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